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Military impacts on some Australian karsts

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Abstract

Karst terrane provides a wide range of important environmental values but is both particularly susceptible to environmental harm and also prominent among those environments where environmentally damaging military activities have occurred globally. Although two Australian karst sites were briefly subject to bombing attacks during World War 2, the most significant known environmental harm caused to Australia's karst by military activity has occurred during the Cold War and in peacetime. This paper reviews persisting legacy issues arising from weapons testing during the 1950s-1960s in two Australian karst areas. It also examines the damage that has resulted from the siting in karst areas of two other military facilities that remain very active today. Further research is desirable into environmental impacts of the operations described in this paper and also into wider aspects of military impacts on Australia's karst environments including offsite effects such as disruption of natural karst process systems related to emissions into the atmosphere and impacts generated by the wider defence industry that supplies and services both the Australian military and weapons export markets.

Introduction

Karst terrane provides a wide range of natural and cultural environmental values and can deliver important ecosystem services, but it is also particularly susceptible to environmental damage caused by human activities. This includes physical harm to landscapes and landforms; disruption of natural geo-ecological processes through disturbance of vegetation, soils and critical hydrological pathways; despoilation of soils through physical disturbance and contamination by water-borne and air-borne chemicals; contamination and other damage to surface and underground waters; and resulting harm to biota and other values that are dependent upon these attributes. Given the values and sensitivity of karst, it is therefore of particular concern that karst has also proven consistently prominent among those environments where military conflict has played out (Halliday 1976, Nunez Jiminez 1987, Day and Kueny 2004, Kiernan 2012, 2013). This is exemplified by current conflicts in the Middle East where karst groundwater beneath the West Bank is a critically important but threatened resource (Rofe and Rafety 1965, Mimi and Assi 2009, Jebreen and others 2018), the asymmetric abstraction of which has itself long been a source of conflict between Israel and Palestine (Walsh and others 2024, Zetoun and others 2009, Mansour and others 2012). Similarly, areas mapped as having been burnt during current conflict in Lebanon (Walsh and others 2024) almost entirely coincide with karst terrane. However, while major environmental harm has typically resulted from conflicts in karst, the environmental impacts of actual conflict are only part of the story because significant environmental impacts that derive from preparations for war, such as weapons manufacture, weapons testing, and military training activities, must also be taken into account (Kiernan 2021a). Australia's karst areas have not been immune from such military impacts. Recognising and understanding the damage caused by military activities in Australia, and its implications, is a necessary precursor to stemming further harm to Australia's karst estate from this source. This paper reviews some of these Australian sites and synthesises some of the key issues, based on accessible literature and supplemented by some fine-tuning based on more recent reconnaissance-level field observations by the author at some of the key sites addressed.

Desirable as it may be, it would be unrealistic to expect the environment to be front of mind in the immediacy of actual conflict, especially when decisions need to be made rapidly and an opposing force unconcerned about its environmental impact may effectively be setting the stage and the agenda. The less pressured pre-conflict and so-called "post conflict" times seem more permissive of environmental concerns being given greater regard. Indeed, many militaries now employ environmental specialists to guide more sensitive use of training areas or to safeguard against pollution, although there are limits as to what can be achieved if military or political directives are prioritised over all other concerns. However, specific provision is commonly included within national environmental protection legislation for exemptions where military activities are involved (Cottrell 2025). For example, Article 2(1) of the European Parliament and Council's *Regulation (EC) No 1907/2006,* which seeks to control the use of certain chemicals, provides for exemptions "where necessary in the interests of defence" (European Union 2006). In the USA, where military expenditure exceeds the GDP of all but 24 countries worldwide, most major environmental legislation, such as the *Endangered Species Act* and *Migratory Bird Act*, allows for exemptions for military activities (Smith 2019). Similarly in Australia, Section 158 (5) of the *Environment Protection and Biodiversity Conservation Act 1999* provides for the Minister to grant exemptions for military purposes. Nevertheless, Australia's *2016 Defence White Paper* (Australian Government 2016) affirmed at section 4.71 that "Effective environmental management is an important part of successfully managing and ensuring the long-term sustainability of the Defence estate. The Government expects Defence to take its environmental stewardship responsibilities seriously, and to comply with relevant environmental legislation and regulations, including the protection of biodiversity on Defence bases". Australia is in the fortunate position of having a Department of Defence that is today relatively responsive to environmental concerns, but this also needs to be balanced against achieving its foundational defence and capability functions (Defence 2020).

While battlefield actions by an opposing force are largely beyond the control of any military, nation states do have the capacity to limit environmental harm by careful selection of sites where they choose to locate facilities that may attract attack or where weapons testing or other military preparations are undertaken. Both the 1954 *Hague Convention for the Protection of Cultural Property in the event of Armed Conflict*, and new United Nations International Law Committee (ILC) draft principles designed to improve environmental protection during armed conflict, limit protection to sites that do not contain a military objective. Hence, if states wish to reduce potential harm to their special places, such as karst areas, then the onus is on them not to establish military facilities there. Two Australian karst sites came under attack during World War II due to the presence of bases there. Weapon testing has occurred at two further karst sites in earlier times when awareness of environmental concerns was much less developed than now. Some legacy issues in relation to these sites are considered in this paper. In addition, major military installations presently operate in two other karst locations, both of which have impacted upon karst groundwater resources and also make those sites legitimate targets for military attack should conflict occur. Some new military facilities are also being established on or proximal to Australian karst sites. The potential for environmental damage that may be caused by accidents involving materials in use at military establishments also warrants consideration.

The scope of post-conflict environmental assessments compiled by UN agencies is typically limited to contaminants or harm to biota (eg. UNEP/UNCHS 1999, UNEP 2004, 2007), but the geo-environment is now also beginning to receive some regard, including by some influential non-governmental organisations such as the UK-based Conflict and Environment Observatory (CEOBS) that aims to enhance the recognition of war's environmental harm, the documentation and understanding of that harm, and the development of improved international protocols (Kiernan 2021b, Watson and Shekhunova 2025). Karst figures significantly in a recent CEOBS report concerning the impacts on geodiversity of the current war in Ukraine (Watson and Shekhunova 2025). However, a similar approach to assessment of non-conflict phase military activities is also warranted. Such lessons as may be learned of past impacts on karst might usefully inform efforts to reduce the damage that might otherwise be caused to karst areas in the future. To this end, this paper examines the Australian experience.

Legacy sites

1.Montebello islands

The Montebello archipelago lies just off the Pilbara coastline of north-western Australia, about 120 km from the industrial port city of Dampier. It comprises about 170 small limestone and sand islands with a combined land area of about 22 km^2. The two largest islands are Hermite (1022 ha) and Trimouille (522 ha). Its military history includes having been the site of the first atomic bomb testing conducted in Australia, from which a significant legacy of environmental harm persists.

The karst connection

Modern coral reefs are commonly formed on older coastal (carbonate) ridges, and the submerged palaeoshorelines off NW WA are among the longest known anywhere. The Montebello Islands rest upon the same carbonate platform as underlies the larger Barrow Island, 20 km further south. However, while the low and undulating Barrow Island is almost entirely middle Miocene limestone (Trealla Limestone) similar to that in the Cape Range, 150 km further south-westwards, this unit does not crop out above sea level on the Montebellos, where only Quaternary calcarenites similar to those that fringe much of Barrow are exposed (Hocking and others 1987, Lebrec and others 2023).

While the presence of carbonates has been recorded in mapping by the Geological Survey of Western Australia, prior to this paper no previous recognition of karst being present in the Montebello islands is apparent in the mainstream Australian karst literature (eg. Matthews 1985, Jennings 1987, Finlayson and Hamilton-Smith 2003, Webb and others 2023). However, semi-circular bays that are almost disconnected from the sea, particularly evident along the contorted shoreline of Hermite Island, bear a striking similarity to the shoreline configurations of drowned towerkarsts elsewhere and are most probably drowned karstic depressions (Figure 1). Sea level was much lower than now during the Glacial Climatic Stages of the late Cainozoic when considerable volumes of water were locked in ice sheets and glaciers. At these times the Montebello islands, together with the larger Barrow Island (234 km^2), now a low (65 m) undulating continental island, would together have

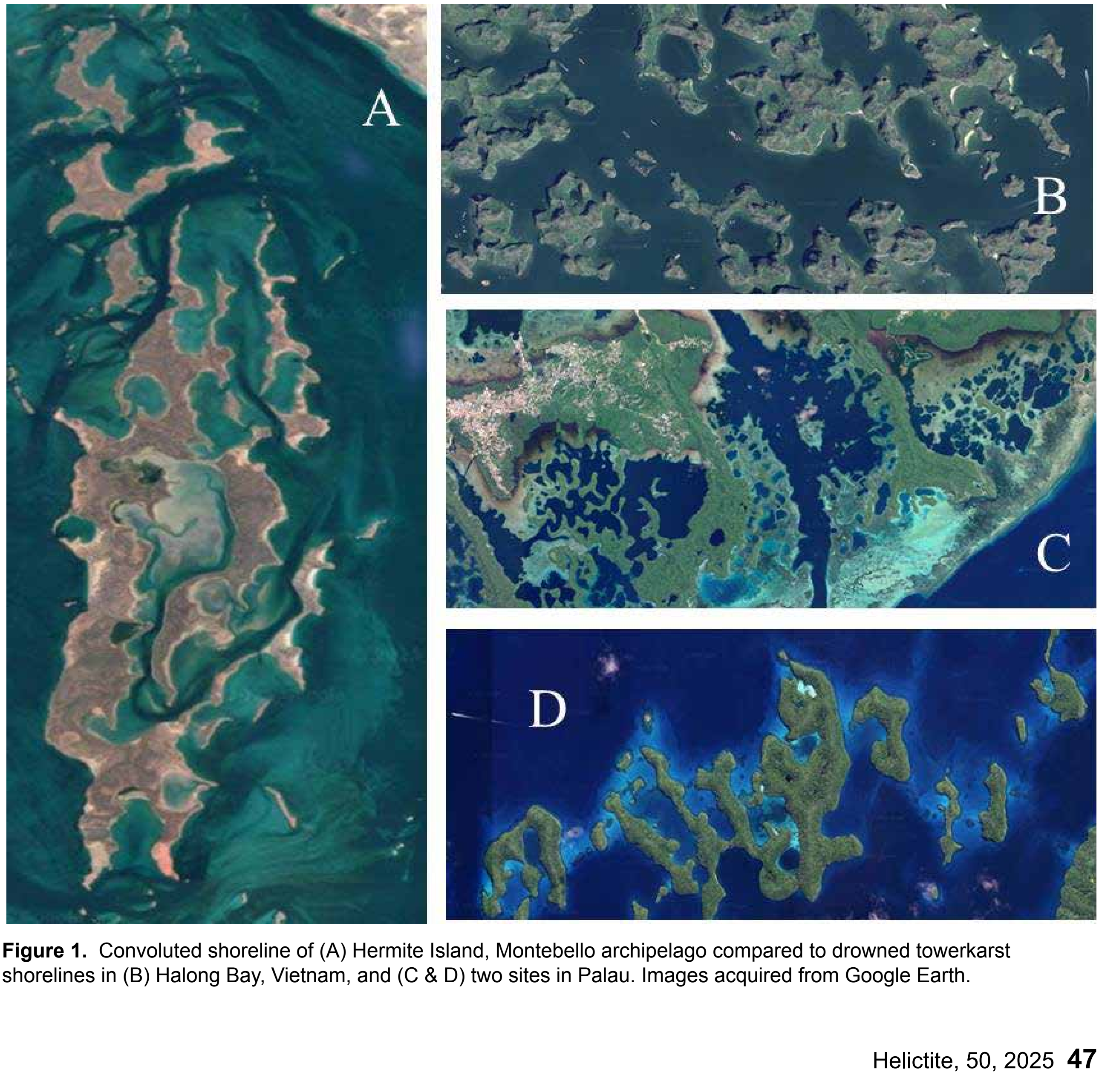

Figure 1. Convoluted shoreline of (A) Hermite Island, Montebello archipelago compared to drowned towerkarst shorelines in (B) Halong Bay, Vietnam, and (C & D) two sites in Palau. Images acquired from Google Earth.

formed a low range of hills rising from a coastal plain. The resultant lower base level of vadose erosion would have allowed vigorous karstification. Notwithstanding the submerged blue holes of the Great Barrier Reef, the Montebello karst may represent Australia's only example of this sort of karst landscape that is above sea level today – even if it is only just above sea level.

Adding to the significance of this karst are several caves that have been investigated for their archaeological contents but without their wider karst system context having been recognised or addressed. The oldest known occupation deposits, in Noala Cave on Campbell Island, have been dated to 27,220 ± 640 BP (Before Present) (Veth and others 2007). Hence, this occupation occurred during the most recent episode of lower glacial-stage sea level. Potentially adding to the picture, the Montebellos lie less than 150 km from the extraordinarily rich archaeological sites of Murujuga/Dampier Peninsula on mainland Australia that were accorded World Heritage status in mid-2025. For most of Australia's human history its land mass was much more extensive than at present, up to 25% of the continental area then becoming inundated by the postglacial sea level rise responsible for today's shoreline. During the Last Glacial maximum the coastline would have lain about 160 km further offshore from Murujuga than is presently the case. Research into the drowned archaeology of this Murujuga "Sea Country" is in its infancy, but preparatory work involving satellite-derived bathymetric and multi-beam echo sounder datasets undertaken between the predominantly granitic islands of the Dampier Archipelago has revealed notch and visor slope profiles eroded into now-submerged carbonate rocks, that are typical of those that form along rocky limestone coasts, and numerous drowned closed depressions. When these data were revealed to the local Ngarda-Ngarli indigenous people, senior elders immediately recognised one pair of depressions as forming part of their Kangaroo song-line, oral tradition having preserved memory of this now hidden topography through many millennia (Kearney and others 2023). Stone tools were subsequently found associated with a submerged freshwater spring in one of these underwater enclosed depressions (Benjamin and others 2023). These findings highlight an inconsistency between the living cultural connection and actual cultural landscape versus the artificial cadastral boundary of what is now the Murujuga World Heritage site, which appears to have been drawn such as to encompass only the islands above present sea level and which consequently incorporates only that portion of the sea country that fortuitously occupies the interstices between them. The earliest cultural deposits in the Montebello caves contain remains of mainly terrestrial fauna, but with a marine component to the diet of the cave-dwellers later becoming more evident up to the time when rising sea levels saw separation of the Montebellos from the mainland and then from Barrow Island about 7000 years ago (Veth 1993, Veth and others 2007). While there is no reason to assume continuous karst between Murujuga and the Montebellos, it seems reasonable to consider a contiguous cultural landscape likely existed, and that undersea karstic archaeological sites likely also exist around the Montebello islands.

Military activities

Unwilling to conduct atomic bomb testing at home, Britain settled on Australia, where it had been testing rockets at Woomera since 1947. A request to use the Montebello islands was made within one year of Robert Menzies becoming Australian Prime Minister, and he unilaterally agreed to the request over the course of a single weekend (Tynan 2022, Grace 2023). Around the time of the first Montebello test there was concern in Britain about the possibility of a bomb being smuggled to a target in a ship, hence it was resolved that the first test, known as Operation Hurricane, should also facilitate assessment of the potential effects of this by deploying the 25 kt bomb 2.7 m below waterline in the hold of *HMS Plym* in October 1952. Operation Mosaic in 1956 involved above-ground tests designed to obtain knowledge to assist in moving beyond a fission bomb towards a fusion device, by using fusion to supplement fission. The initial experimental Mosaic G1 on northernmost Trimouille Island yielded a 15 kt blast with a minimal fusion contribution. Mosaic G2 was detonated on a 33 m-high tower on Alpha Island. It was reported as having been 60 kt but revealed in 1984 to have actually been 98 kt, about six times the size of the bomb dropped on Hiroshima and very much larger than had been agreed upon in an undertaking given to PM Menzies by British PM Eden that no future test would exceed twice the yield of the Hurricane blast. It has more recently emerged that Britain began work towards an H bomb in the mid-1940s and that this work continued in tandem with its atomic bomb testing, despite repeated assurances that it would not test thermonuclear materials in Australia. In his 1961 memoir former British Prime Minister Anthony Eden acknowledged that his government decided in 1954 to make a hydrogen bomb (Eden 1961). By late 1955 the British were working on placement of a trigger bomb inside a common outer case with radiation-transmitting material between them. This detonation was boosted by using a light element (uranium) rather than the lead tamper used previously, effectively a stepping stone towards a thermonuclear device (Arnold 1987, Arnold and Pyne 2001, E. Tynan pers. comm.).

Environmental impacts and legacies

The environmental damage inflicted on this karst by weapons testing included both physical damage and chemical contamination of soils and water. The water beneath *HMS Plym* was about 12 m deep and the 25 kt. bomb left a sea-bed crater about 6 m deep and 300 m diameter that remains discernible. The extent to which fractures may have been created in the bedrock below the detonation site, into which radionuclides may have been able to gain access deeper into the karst, remains unknown. However, it is important to note that there is no reason to expect that the sort of serious physical geological damage that was reportedly caused by French nuclear testing in the Pacific atolls of Muroroa and Fangataufa between 1966 and 1996 might also have occurred at Montebello because the two situations are in no way comparable. The damage in the Pacific was related to 137 underground tests within cavities excavated into volcanic rocks beneath these Pacific atolls, twelve of them causing formation of a chimney into the carbonates through collapse of the underground nuclear explosion cavities, potentially releasing tritium, strontium and caesium into the karst groundwater. An additional four tests released tritium into the karst despite expectations that volcanic cover rocks would contain contaminants. It was an accidental blast at only 400 m depth that reportedly caused the 2 kilometre-long and 40 cm wide crack that appeared on the atoll. Of the 41 atmospheric nuclear tests conducted by France only the first three involved detonation on barges similar to Operation Hurricane (Chiappini and others. 1999), but there seems to be no accessible data concerning their impacts on the deeper substrate that might offer any insight into possible effects of the blasts in the Montebellos. The remainder of the French atmospheric tests are also not comparable because they often involved much larger bombs than that detonated during Operation Hurricane and they were mostly detonated while suspended above ground-level beneath balloons.

Nevertheless, coral was obliterated by the Hurricane detonation. Whether any subsea karstic archaeological sites around the Montebellos may have been impacted remains unknown. Contemporary reports also indicate that detonation caused a massive wave to sweep across the islands. However, the significance of the environmental damage this wave caused needs to be considered in context with Bureau of Meteorology records of natural tsunamis along this part of the Australian coast, most recently reaching 6 m above sea level in 1977 locally, and extending 300 m inland in 1994. Another in 2006 locally reached 200 m inland, causing extensive erosion and vegetation damage and sweeping away coastal campsites on the mainland. The geological record hints at tsunamis up to 20 m high in the more distant past (Scheffers and others 2008, Playford 2014). Hence the Operation Hurricane wave damage appears likely within the bounds of natural events, and while it may have up-ended the natural rehabilitation of any preceding tsunami damage its physical effects are likely to have been surpassed by those of natural tsunami waves since the tests were concluded. However, radioactive materials left on and around the Montebello Islands are likely to have been distributed more widely into the marine environment by subsequent natural waves.

The tests also caused widespread distribution of airborne contaminants across the Montebellos and possibly even more distant karsts. Despite a fallout cloud from Operation Hurricane blowing across north-western WA, the safety committee reported to the Australian government that the required conditions were “fully met" (Walker 2014). Fallout from Operation Mosaic again spread across the mainland coast, the first public alert coming not from government but from a prospector in the Pilbara area who contacted a newspaper regarding his Geiger counter having gone off the scale. Fallout levels exceeded safe limits in places like Derby, Port Hedland and Broome (Tynan 2016). The government moved swiftly to silence the news, Supply Minister Beale much later revealing that the issue nearly led to his dismissal from his portfolio (Beale 1977). Excessive iodine-131 levels (^{131}I) in sheep and cattle grazing on grass subject to fallout were detected as far afield as Rockhampton (Cross 2001), but the putative safety committee was unresponsive. A 1985 Royal Commission found that the safety committee’s positive report about the Mosaic tests was “grossly misleading and irresponsible” (McClelland and others 1985).

Considerable aeolian redistribution and mixing of radioactive material is also likely since the tests occurred. The Montebello area is highly exposed to extreme weather events, the strongest non-tornadic wind gust ever recorded on Earth (408 kph) having swept adjacent Barrow Island in April 1996.

Instantaneous devastation of the natural biota proximal to the detonations would seem inevitable. Many dead turtles were reported the year following the Hurricane detonation. Other potential impacts on the natural biota remain open to conjecture but, by analogy with demonstrated detriment caused to human health, longer-term harm would also appear likely. A disproportionately high rate of cancers have been reported among servicemen involved in the Montebello tests. Notwithstanding government reluctance to admit potentially costly legal liability, the probability that these cancers were caused by exposure during the bomb tests has effectively been acknowledged by the Australian government through its provision of some compensatory medical measures (Weber and Piesse 2017, Kagi 2018). In early 2024 formal proceedings were launched against the UK Ministry of Defence by surviving UK veterans alleging negligence in its duty of care to both the veterans and to their families before, during and after the tests that began at the Montebellos. It might reasonably be assumed from these health issues suffered by these people, who were present there only briefly, that the longer-term resident natural biota of the archipelago was also adversely affected. As part of a small archipelago elsewhere renowned for their coral reefs and marine life, the test sites are now managed by the WA Parks & Wildlife Service, which advises that no more than one hour should be spent ashore, that relicts should not be handled, and that soil should not be disturbed.

No significant clean-up of the site was ever undertaken, nor any study of its radiation levels. Infrastructure from the tests remains, together with large fragments of *HMS Plym* located many hundreds of metres from the blast site. A report from the Australian Radiation Laboratories published in 1979 found that radiation in soils on Alpha and Trimouille islands remained above safe levels for continuous occupancy. Traces of cobalt 60 (^{60}Co) were detected in marine organisms and traces of several radionuclides were detected in vegetation around the ground zeros (Cooper and Hartley 1979). Residual plutonium (Pu) was reported in 2013 (Child and Hotchkis 2013). While activity levels of the fission and neutron activation products have decreased markedly, Pu levels remain elevated in soils, sediment and biota, with uptake of radioactive isotopes demonstrated in several terrestrial and marine animal species (Johansen and others 2019). Recent studies have found radioactivity concentrations to the northwest that presumably reflect the original fallout plumes. The highest remaining concentrations of strontium-90 (^{90}Sr), caesium 137 (^{137}Cs), ^{238}Pu, ^{239} Pu and ^{240}Pu in surface sediments were found in the northern part of the archipelago. However, a location 26 km south that was originally selected as an environmental control site revealed higher concentrations of ^{90}Sr (121 Bq/kg), ^{137}Cs (1.6 Bq/kg), ^{238}Pu (80 Bq/kg), $^{239\ \&\ 240}Pu$ (402 Bq/kg) and Americium ^{241}Am (28 Bq/kg) in comparison to other locations in the archipelago. A core from the base of the Hurricane crater formed beneath *HMS Plym* retained ^{137}Cs and ^{241}Am concentrations three times higher than in adjacent surface sediments (Williams-Hoffman and others 2022). Radioactivity levels may have been sufficiently high as to prove lethal to sea turtles for a decade after the tests were conducted, and the present population may carry some of the genomic legacy. Tests conducted in 2019 still found elevated radiation levels in sea turtle skin, bones, egg-shells, embryos and hatchlings, and in some of their diet items. The sands in which turtle eggs are deposited to develop and hatch retain elevated radioactivity levels throughout the depth range to which prospective turtle parents excavate for this purpose (Johansen and others 2020).

2. Maralinga

The Maralinga area lies in the Great Victoria Desert and was the site of British nuclear testing from 1955 to 1963. The detonations took place on the Tietkens Plains karst, which is located 175 km NNE from the head of the Great Australian Bight and 850 km NW of Adelaide. The Tietkens Plains karst is topographically very similar to the more celebrated Nullarbor karst to its south, from which it is separated by a range of hills named the Ooldea Range. The following comments are based upon accessible literature, the author's personal observations on Tietkens Plains in late 2022 and on various previous field trips to the Nullarbor.

The karst connection

The Tietkens Plains karst is formed within the 10-20 m-thick Garford Formation dolomite which was deposited during the Miocene. The dolomite is commonly obscured by aeolian sands from the Great Victoria Desert, upon which a calcrete layer up to 1 m thick has developed. Surface karst landforms include various dongas, rudimentary karren such as rain pits and solution pans etched into subaerially-exposed outcrops. Notwithstanding the presence of many solution cavities observed in one quarry exposure, surface openings have been largely in-filled by aeolian desert sands and other sediment including palaeokarst infills. Present-day permeability of the dolomite is also likely inhibited by some conspicuous case hardening and recrystallization. Negligible evidence for any significant present-day solutional weathering of the dolomite at Tietkens Plains was detected, consistent with its current aridity. Hence, it appears to be essentially a palaeokarst with a long and varied history.

However, as early as the late 1950s, evidence from 18 water bores between Watson on the northern edge of the Nullarbor Plain and Maralinga, and exposure in the historic Tietkens well (Figure 2) suggested that older limestone also existed deeper beneath Tietkens Plains. Given this, and also their topographic similarity and proximity, some clarification of the relationship between the karst at Maralinga and the Nullarbor karst is warranted.

Figure 2. Garfield Dolomite beds exposed in Tietkens Well No 1.

At least two blowholes are known in the limestone on the southern side of the Ooldea Range but none to its north. In contrast to the dolomite karst at Tietkens Plains, the Nullarbor karst south of the Ooldea Range is formed in limestones of the Eucla Group which represents the largest onshore extent of Cenozoic marine sediments anywhere in the world (Clarke and others 2003). At its base is the 300 m-thick mid-Late Eocene (400-350 Ma) Wilson Bluff limestone, the top of which is a calcrete layer formed after the sea withdrew in the early Oligocene. This is overlain by the Abrakurrie Limestone which was subsequently deposited over only the central part of the Nullarbor, after which the sea again withdrew. The sea then returned to deposit the thin Nullarbor Limestone over most of the plain before it withdrew during the Late Miocene-Early Oligocene. The carbonate units were later uplifted and tilted 100-200 m down towards east (Hou and others 2008).

As at Tietkens Plains, karstification of the Eucla Group carbonates of the adjacent Nullarbor also has a long history. The few humanly-negotiable Nullarbor caves that reach the water table probably originated during the seasonally-wet Oligocene. A distinct band of smaller caves and shallow blowholes 25-30 km wide formed in the Abrakurrie and Nullarbor limestones ~75 km from the present coast, probably as flank margin caves on the mid-Miocene shoreline. Considerable speleothem deposition occurred during the Early-Mid Pliocene (5-3.5 Ma) before the peak of the present arid phase was reached about 1 Ma ago (Webb and James 2023). Discharge from some palaeochannels that originate from the north and west progressively sinks underground. While relatively few large caves can be descended to the water table, the vast majority of the known Nullarbor caves are much smaller and can be negotiated only to shallow depth. However, this relative paucity of large caves is likely due to the high primary porosity of the limestone, and it in no way demands any lack of aquifer continuity. Nor does it necessarily demand complete aquifer discontinuity between the Maralinga area and the Nullarbor should the limestone locally extend further north than its surface exposure suggests.

Much older strata predate the Eucla Basin sediments in this general area, including the world's only known Early Cambrian non-marine oil generated in situ from playa lake source rocks within the Observatory Hill formation, including near the Emu Field test site north of Maralinga (Hibburt 1990). Beneath Maralinga, basal diorite is overlain by about 300 m of shales and sands, interpreted by Ludbrook (1958) as Marinoan (i.e. within the Precambrian) in age, that are in turn overlain by a thin series of grits likely to be either Permian glaciofluvial sediments or Mesozoic sediments containing reworked glacigenic material. Thin paralic Eocene silts and limestones rest upon these (Ludbrook 1958). Gravels and sands at depth within the Pidinga Formation fine upwards progressively to carbonaceous marginal marine and non-marine sediments. Conformably overlying and intercalated with the Pidinga Formation is the Middle Eocene Paling Formation, a carbonaceous limestone comprising ~75% carbonate. It is laterally equivalent to the Wilson Bluff Limestone although not in proven stratigraphic continuity with it (Hou and others 2023).

The Ooldea Range that separates the Nullarbor from Tietkins Plain is not a bedrock ridge but rather a massive ancient coastal sand dune complex 650 km long and located up to 300 km inland from the present coast. It formed at the end of the Eocene, following maximum marine transgression of the Eucla Basin. Together with the nearby Barton and Paling ranges, the Ooldea Range was formed from hinterland sands and may have originated as barrier islands that later amalgamated into dunes parallel to the coast as shoreline progradation continued. Their remarkable preservation for about 35 Ma likely reflects aridity, vegetation cover, the permeability of the sands, subsequent sea level history and basin hydrodynamics (Benbow and others 1982, Benbow 1990, Fairclough and others 2007). The Garford Formation sediments were deposited into a lagoon that was trapped behind coastal dunes produced by longshore drift around the coast of a massive marine embayment similar in form and scale to the present-day Gulf of Mexico in which the limestones of the Nullarbor accumulated (Morris and Benbow 1986, Hou and others 2003, 2008, Holden 2021).

While wholesale continuity of the Eucla Basin north of the Oldea Range has largely been disproven (Ludbrook 1958) the precise inland extremity of the limestones of the Nullarbor at a local level is less certain, but it would have been influenced by the original topography upon which the Eucla Group sediments were deposited. The Maralinga area appears to overlie a now-deeply buried valley that was active during the Cainozoic but was likely initiated considerably earlier. Glacigenic deposits at depth beneath this part of Australia date from the Permo-Carboniferous (Crowell and Frakes 2007, Mory and others 2008, Hou and others 2008, Fielding and others 2023) when glacial and glaciofluvial processes likely eroded multiple and varied re-entrants into the non-carbonate bedrock substrate into which subsequent sediments would have been deposited, including the Cainozoic sequences that that are now targeted by mineral exploration ventures. Any such re-entrants that were unfilled or only partially filled when deposition of the Wilson Bluff limestone occurred would have allowed later localised marine intrusion and deposition of this limestone or facies variants thereof not only beneath Maralinga but perhaps also elsewhere. If the clays between the Garford dolomite and Wilson Bluff limestone equivalents are not continuous, this might theoretically permit linkages between the Tietkens Plains and Nullarbor aquifers anywhere such re-entrants existed.

Military activities

There is no evidence in the accessible literature of karst concerns having been considered prior to the atomic bomb testing program. Many thousands of kilometres of tracks were established across the most remote parts of Australia to facilitate this testing, and the Maralinga area was the epicentre of this landscape modification. In addition to establishment of an elaborate network of local roads, other infrastructure established included quarries, a massive airstrip, the Maralinga township on the Ooldea Range and the outlying Roadside Village on the karst itself. Vegetation removal and earthworks were also conducted around the test sites on Tietkens Plains. Between 1955 and 1963 seven atomic bombs were detonated at different sites at Maralinga, four ranging from 1-15 kt yield during Operation Buffalo from September-October 1956, and three ranging from 1-26 kt during Operation Antler from September-October of 1957. Hundreds of so-called minor trials were also conducted at three sites, under the code names Rats, Tims, Kittens and Vixen. These tests reportedly again focused on neutron activation to trigger fission (McClelland and others 1985). Only relatively recently has it become evident that the trigger/initiation trials at Emu and Maralinga involved field testing of components for thermonuclear bombs tested during Operation Grapple on islands in the Pacific. A perception of urgency at Maralinga is suggested by the fact that when the first Operation Grapple bomb was detonated in May 1957 it established Britain as a nuclear state, just in time to pre-empt planned international negotiations towards establishment of a treaty to stem the spread of nuclear weapons that would otherwise have prevented Britain from joining the thermonuclear club (Arnold and Smith 2006, Rabbitt Roff 2022). The greatest radioactive contamination at Maralinga resulted from the 12 Vixen B tests conducted at the Taranaki site. These involved detonation of bombs in such a way as to avoid a full nuclear detonation, but they nonetheless caused 22 kg of plutonium to be flung nearly a kilometre skywards from the heavy metal structure on which the bombs were placed (Tynan 2016).

Figure 4. Area prepared for proposed test at Tufi site showing anchors for tethering of a balloon-suspended atomic bomb. This particular site was not ultimately used and hence reflects the landscape damage caused merely by site preparation, unmasked by subsequent explosive impacts.

Environmental impact and legacies

The most visually conspicuous environmental impacts of the testing program included development of the Watson and Roadside quarries and gravel pits (Figure 3), and vegetation clearing and excavation for construction of the roads, airstrip, housing and other infrastructure, and of the test sites themselves (Figure 4). This frequently involved incision through the upper calcrete and sometimes into the older carbonate units beneath. The detonation of a 27 kt bomb 300 m above a large donga at the Taranaki site stripped the vegetation and evidence of tree damage is still evident beyond the donga rim. A broad area around the Breakaway site ground zero similarly remains devoid of trees (Figure 5), factors likely to have been contributed to the lack of regrowth including soil removal by the blast, the production of trinitite by vitrification of the remaining regolith surface caused by the blast (Figure 6), and probably volitalisation of soil nutrients. Similar vitrification occurred elsewhere. At Marcoo a 1.5 kt bomb was detonated at ground level, producing a crater 50 m in diameter and penetrating 12 m deep towards the karst aquifer.

Figure 3. Large limestone quarry site at Watson (top) and some of the rubbish dumped into it (bottom).

The karst was also seriously contaminated. The "minor trials" at Taranaki involved dispersal of 22 kg of plutonium, 47 kg of uranium and 18 kg of beryllium. At Wewak about 0.6 kg of Pu, 47 kg of uranium and 4 kg of beryllium were dispersed, while at Naya the corresponding figures are 1.2 kg (0.5 kg of which was collected and returned to the UK), 469 kg and 2.4 kg. Further east at Kuli over 7000 kg of natural and depleted uranium and 75 kg of beryllium was dispersed between 1956-63 (James and Williams 1989), while 28 kg of uranium was dispersed around Dobo. Many other contaminants such as asbestos were also left scattered over a wide area after the British left, together with numerous contaminated vehicles and a great deal of contaminated plant and equipment. British attempts to "dilute" the contamination prior to their departure included ploughing of the ground surface to break up the trinitite (Figure 7).

Figure 5. Extent of blast-pruned vegetation surrounding Breakaway site ground zero, as at 2023.

Figure 6. Trinitite produced through vitrification of the soil surface by the atomic bomb detonated at the Breakaway site.

Figure 7. Soil surface subject to ploughing by the British prior to their departure, to "dilute" radioactive contamination by breaking up the trinitite, which greatly complicated subsequent environmental remediation attempts.

In the late 1970s concern was expressed by Australian Defence Minister Jim Killen that the plutonium might be retrieved by communists and should be better secured (Toohey 1978). Britain secretly removed a small quantity in February 1979 but insisted that Australia pay for that exercise. In 1984 the Hawke government established a Royal Commission to determine the condition of the sites and their suitability for return to their traditional owners. In its report released in 1985 (McClelland and others. 1985), the Commission recommended major clean-up of the contaminated sites. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) advised the Royal Commission that an estimated 25,000-50,000 contaminated fragments likely remained around Taranaki (Tynan 2016). In 1993 it emerged that the US Roller Coaster program in Nevada in 1963 had involved a series of non-nuclear detonations of Pu-bearing weapons similar to Britain's so-called "minor trials" in Australia, and when the results were declassified it enabled re-estimation of the degree of contamination in Australia. It had been under-estimated by a factor of about 10 and this must have been known to the British who never conveyed this information to Australia (Anderson 1993). During the clean-up, undertaken from 1995 to 2000, contaminated surface soils were stripped from extensive areas and buried in pits. A trench 15 m deep, 205 m long and 140 m wide was excavated at the most heavily contaminated site, Taranaki, filled to within 3 m of the top with debris, and then covered with 6 m of uncontaminated soil (Figure 8). An estimated 3.3 kg of Pu was contained in the 220,000m^3 of soil scraped up and deposited into the trench. The crater at Marcoo was filled with contaminated debris.

Some information concerning the geology and hydrogeology of the Maralinga area was available prior to the latest clean-up (Morris and Benbow 1986) and a brief examination of the Tietkens Plains karst was also undertaken (James and Williams 1986). However, a report compiled by the Maralinga Rehabilitation Technical Advisory Committee (MARTEC) upon completion of the clean-up program makes virtually no mention of this information having been effectively brought to bear during design of the project, and no reassessment of impacts on the karst caused by either the tests or the clean-up exercise appears to have been undertaken over

Figure 8. Debris capping over shallowly buried contaminated materials at the Taranaki site.

the subsequent quarter century. The Hansard record of responses to questioning of one expert witness during Australian Senate's Supplementary Estimates hearing on 3 May 2000 (Commonwealth of Australia 2000) is less than reassuring:

Senator ALLISON—…At page 8 of the attachment, Mr Davy says: The burial pits contain the contaminated materials at levels well below the base of the limestone ... How accurate is that statement, Mr Harris?... It states: The burial pits contain the contaminated materials at levels well below the base of the limestone ...

Mr Harris—We believe that is accurate.

Senator ALLISON—You believe that is accurate. Isn't it the case that the debris is only two or three metres below the top of the limestone, not at the base of it?

Dr Perkins—The limestone is the rock at the top of a thick sequence of flat-lying sediments. I think Mr Davy was referring to the upper crust of limestone. Beneath that there is a very solid sequence of limestone, sandstone and mudstone. It is a very stable bedrock environment.

Senator ALLISON—Indeed, but how could you say that it is well below the base of the limestone when it is just under the top?

Dr Perkins—I think what Mr Davy was referring to was the very top part of the limestone sequence.

Senator ALLISON—No. He says `well below the base of the limestone'. It is quite clear.

Dr Perkins—Yes. He is saying `the base of the limestone'. It is a thin sequence, say, of a metre or so. The base of the limestone is the cap, but there is a thick sequence of sediments underneath.

Senator ALLISON—A different kind of limestone?

Dr Perkins—Yes, that is right. There are limestones and limestones, but it is a layer of solid, stable rock.

Notwithstanding that the development of subsurface karstic plumbing requires the action of water and Maralinga is presently an arid/sub arid environment where sand blown across the bedrock plains from the Great Victoria Desert further north further insulates the bedrock in some ways, it does still rain sometimes. Subsidence of some burial pits may reflect either compaction and settling, or the opening up of karstic voids due to material being flushed away from the excavation base. Hence, one cannot be entirely sanguine about the risks of contaminant dispersal through karstic conduits, nor perhaps potential local connectivity between conduits formed in the Garford dolomite and Wilsons Bluff limestone.

Dumping of contaminants into the Marcoo crater and excavation of the ditch at Taranaki brought contaminants closer to any unsealed palaeokarstic conduits in the dolomite or underlying limestone. It is also worth noting in the context of Marcoo that there is compelling evidence from battlefields elsewhere in the world for the detonation of even merely conventional bombs having triggered the formation of sinkholes due to bomb craters forming a focus into which runoff subsequently occurs, through the detonation having created new fractures in the bedrock that are susceptible to solutional enlargement, or by a combination of the two (Celi 1991, Kiernan 2013).

The potential for redistribution of contaminants across the karst by strong winds might also usefully be considered. Questioned in a senate hearing in May 2000, the head of the Coal and Minerals Industries Division within the Department of Industry, Science and Resources was dismissive, conceding only "that it may be that some grams of soil blew away" (Commonwealth of Australia 2000). But in arid Australia strong winds and dust clouds are common, and at Taranaki more than just "some grams" so impeded visibility that the clean-up work had to cease on 15 occasions, and once caused complete evacuation of the area (Parkinson 2007). Some of the dust blew back onto cleared areas. Dust was better suppressed at other sites later. On the windy Nullarbor proper there are low parallel ridges that are believed to be the etched footprints of previously extensive desert dune systems, since blown away (Webb and James 2023). The subdued surface topography on the Nullarbor proper may favour relatively rapid transmission rather than long-term deposition of material entrained by the wind. Sinkholes and caves typically provide more effective aeolian sediment sinks. While the Ooldea Range partly impedes the spread onto the Nullarbor karst of sand blown from the Great Victoria Desert, the same may not be true for finer particles transported higher in the airstream. Analyses of a few samples from within some of the typically dusty Nullarbor caves might be informative.

Figure 9. Drainage channel condition indicative of significant present-day rainwater runoff from the southern side of the Ooldea Range.

When subject to physical and chemical weathering, Pu particles can be mobilised in solute or particle form, dispersed by water and taken up by plants and animals (Ikeda and others 2016). Research published in 2021 revealed that "hot" particles persisting at Maralinga, most likely formed by cooling and condensation of poly-metallic melts within the detonation plumes, occur as micro-nano particles. Some are inherently friable and most are susceptible to weathering, which in the arid desert environment at Maralinga is likely to be primarily mechanical, breaching their hard outer shell and facilitating the subsequent redistribution of the radioactive materials by water or as dust. When taken up by plants or soil biota that are eaten by animals it will accumulate (Cook and others 2021).

The aquifers beneath Maralinga may not all be palaeokarstic because Maralinga is not entirely dry. Short intense rain-showers can covert dry dongas into short-lived lakes, subsequent drying of which probably involves a combination of infiltration into the karst, and evaporation such as has been fundamental to calcrete formation. Moderately well incised drainage channels have been cut by runoff on at least the southern flanks of the Ooldea Range (Figure 9), and substantial water-bodies form at its foot on occasions. While hugely diminished since Pliocene times, the precipitation of dripstone speleothems has not entirely ceased beneath the Nullarbor and nor are karst processes likely to be entirely defunct beneath Maralinga. In addition, it has previously been suggested that some of the Nullarbor karstic features were not formed by meteoric water that descended from the ground surface but instead by water that rose up from beneath (Lowry 1967). The reported breaching of at least one blowhole during construction of a road where no naturally open holes now exist (James and Williams 1988) emphasises the likelihood of continuing water movement through subsurface karst. Numerous subsurface solution cavities are evident in limestone exposed by quarrying on the northernmost Nullarbor at Watson and further east at Rawlinna, areas subject to similar long-term aridity as Tietkins Plains. Many are entirely filled with palaeokarstic sediments or younger red desert sands but others are only partially filled, and open solution cavities and fractures occur beneath and laterally adjacent to some of these infills (Figure 10). Blockage of subsurface conduits in the Maralinga area may well be similarly incomplete and some of the blockages that exist might yet be flushed out again in future, either due to the occasional intense rains or perhaps even in response to climate change.

Given the subsurface solution features and interstratal and fracture permeability evident in the limestone quarries, it is apposite that the material buried at Maralinga is varied and was not sealed. Some interactions recorded in Hansard from the Australian Senate's Supplementary Estimates hearing on 3 May 2000 seem potentially apposite:

Senator ALLISON—This option of concrete encasement is something that was floated in the options in the TAG report, was it not? Why has it suddenly become impractical?

Mr Harris—Yes, it was one option. But again we are looking to the outcome, and the process that we went through and the way we designed the burial trench has been approved by ARPANSA…the burial trench also has a couple of layers of plastic

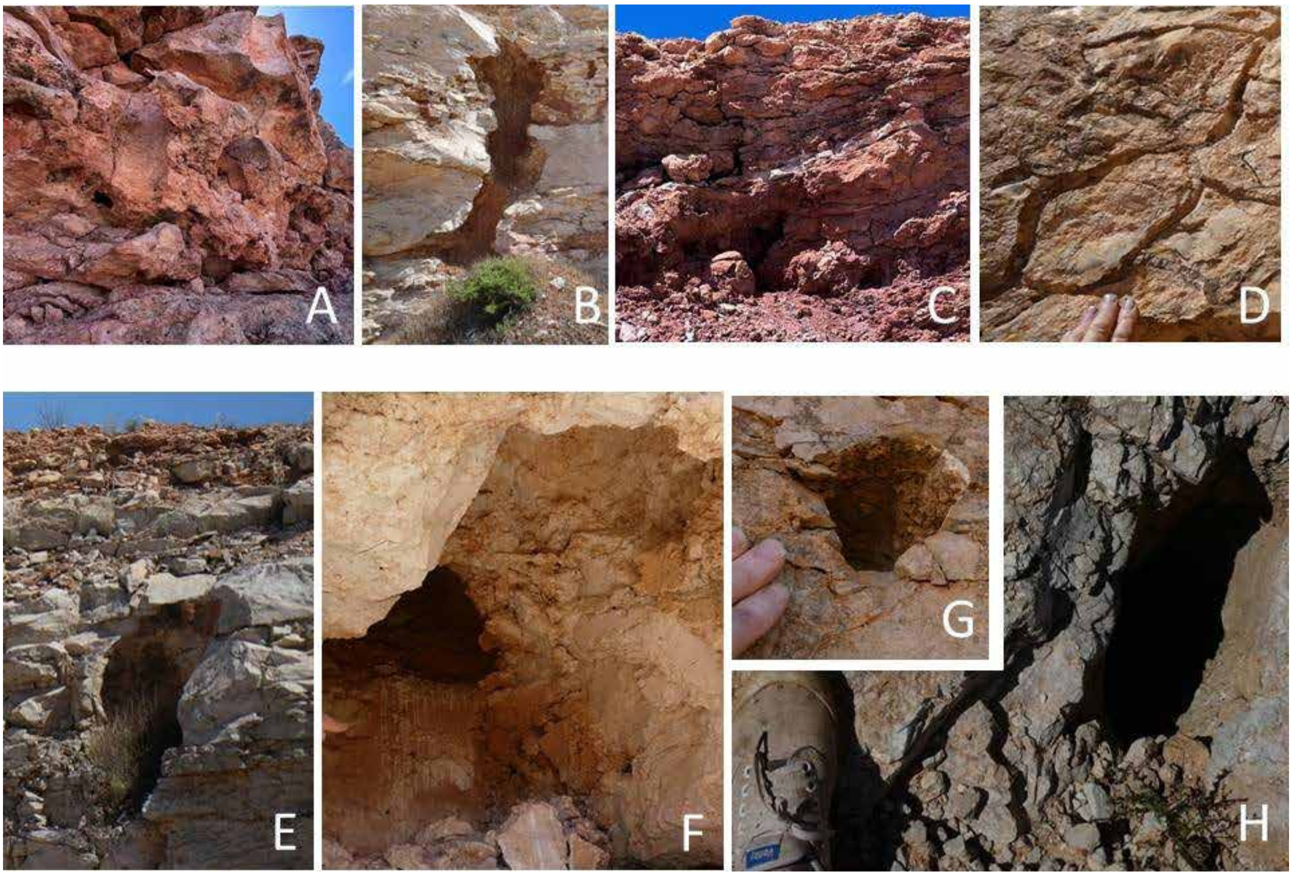

Figure 10. Quarry exposures of subsurface palaeokarstic and desert sand fills in solution cavities (A. Watson, B. Rawlinna); generally fractured condition of the limestone (C. Watson); open solution half tubes (D. Watson); and other open voids (EFGH. Rawlinna)

to clearly identify for people who are wanting to intrude in that trench that they ought to pay attention to what they are doing. That is in addition to the signs that are placed around the trench and to concrete plinths that we are putting at the location.

Senator ALLISON—Just as a matter of interest, what is the life of the plastic?

Mr Harris—I can only tell you that we got some heavy duty plastic, and I think it is a few thousand years.

Senator ALLISON —A bit of plastic lasts a few thousand years? Fascinating.

Dr Perkins —We have a more durable marker horizon, a layer of vitrified block material that will last for a considerable time in a geologic sense.

[later:]

Senator ALLISON—If we can talk about the codes, you said in your press release, Minister, that the project had been conducted in a manner consistent with both international guidelines and domestic codes of practice. In your release on 17 April you said:

"Whilst the government was under no obligation to refer to the NHMRC Code of Practice for the near-surface disposal of radioactive waste in Australia (1992) as the Code was not specifically designed for a situation like Maralinga where there already was contamination, in the interests of enhancing safety, the Government elected to observe the Code".

[then later again:]

Senator ALLISON—… The code says in clause 2.3.3(a):

Radioactive waste shall not contain corrosive materials, waste containing … alkalis shall be treated to neutralise them.

As I understand it, 60 tonnes of soda ash, which is both a corrosive and an alkaline substance, from Ceduna was dumped in the burial pit. Was that material neutralised?

[then later:]

Senator ALLISON—I will read that clause to you again. It says that radioactive waste shall not contain corrosive materials, and waste containing alkalis shall be treated to neutralise them. Doesn't that suggest that you do not put those two substances together?

Mr Harris—What could be observed is that the limestone environment at Maralinga is an alkaline environment which has a natural neutralising effect on the soda ash.

Senator ALLISON—In 60-tonne quantities? How would it do that?

Mr Harris —There is a lot of limestone out there.

Senator ALLISON—How does it get to 60 tonnes of soda ash? Did you mix it with limestone as you put it in? That is my question. Did you neutralise it?

Mr Harris—It is fully surrounded by this sort of limestone material that the burial trench has been filled in with.

Senator ALLISON—Being surrounded by it does not mean it is necessarily neutralised, does it?

Mr Harris—I would have to refer to experts on how chemical reactions take place in an arid environment.

Just as a globally distributed layer of iridium produced by asteroid impact has been adopted as a marker for the end of the Cretaceous, so too does globally distributed radioactive fallout from bomb testing offer a potential marker bed for commencement of the Anthropocene, in which case Maralinga would be a contender for being the type site for Australia (Holden 2021, Burrows and others 2023). Regional aerial radiometric survey packages available from the South Australian Resources Information Gateway (South Australian Resources Information Gateway 2024) show various concentration points across this part of South Australia (Figure 11). Interpretation is complicated by the fact that there are naturally high levels of uranium in the Gawler Craton and in sediments derived therefrom (Hou and others 2023). However, elevated levels at the actual Maralinga test sites can reasonably be attributed to the testing there. Apparent concentrations further east conceivably involve natural occurrences rather than downwind fallout, but there is also a marked concentration 120-130 kilometres upwind of the test sites at the 20 km-wide Carle Thulka (Lake Maurice) and in a smaller lake basin 8 km to its north, both being located within a low point within Tietkins Plain.

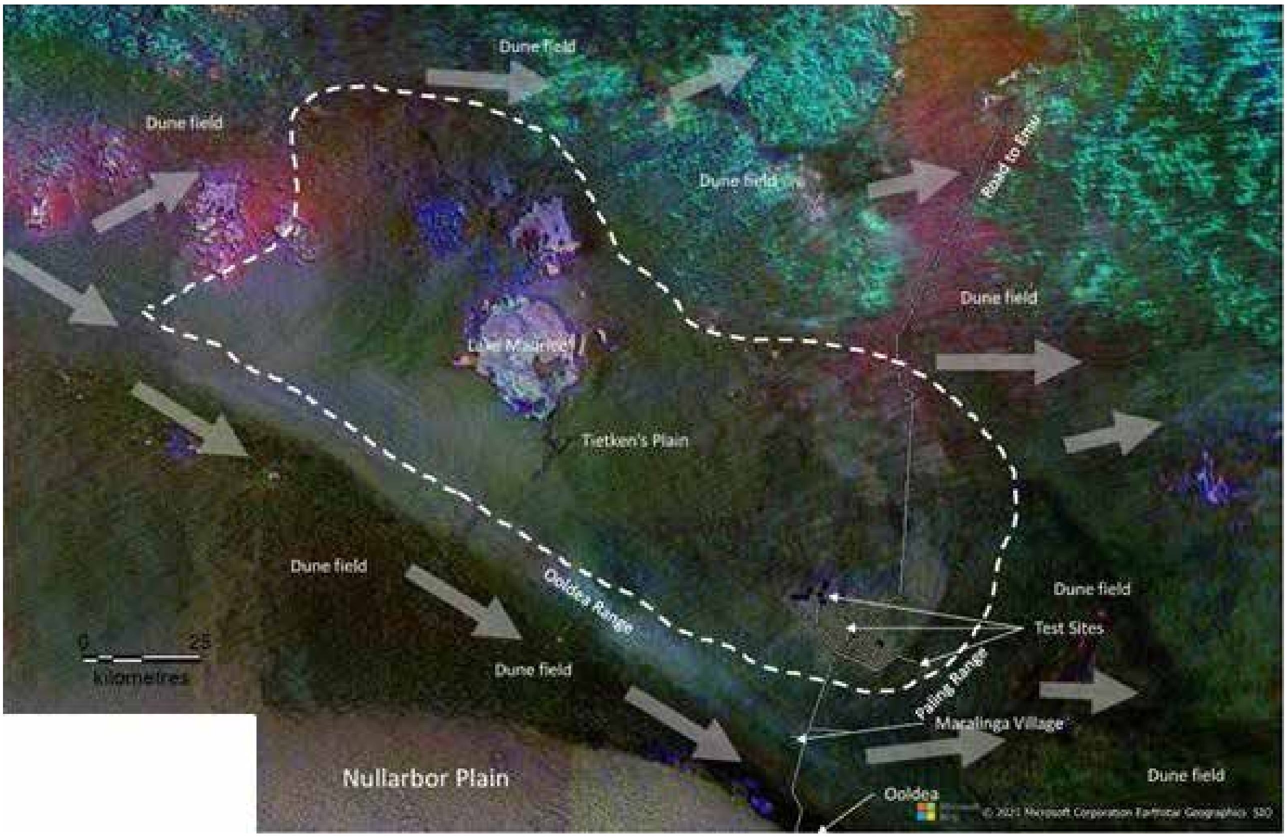

Figure 11. Portion of 2017 Gawler Craton Radiometric Survey (PRSA), showing radiation evident in Maralinga area (blue = uranium; green = thorium; red = potassium) and predominant wind directions (broad arrows), from Holden 2021. Most concentrations are natural occurrences but the concentrations around the bomb testing sites and Carle Thulka (Lake Maurice) are noteworthy.

Although a natural explanation for this cannot be discounted, carriage of radionuclides by waters from the test sites is also a possibility. Given that no linking surface plume extends between the test sites and the Carle Thulka area, the possibility exists that the isolated concentration in the latter area is due to evaporation from a point at which deeper karstic groundwater emerges (Holden 2021).

As in the Montebellos, no baseline data is available against which the impacts of bomb testing on cave biota might be assessed, but once again, documented impacts on human health suggest harm is likely. Prior to establishment of Maralinga, tests were also conducted 150 km further north at Emu Field. The Totem 1 test on 14 October 1953 occurred under windy conditions and produced a mushroom cloud that rose to only half the predicted height. While some Aborigines frequenting the test site had been forcibly removed to a refugee camp at Yalata further south, where some of their descendants still reside, others living to the northeast of Maralinga reported a mysterious “black mist” slowly rolling across the area and coating all in a greasy film. At least 45 people from the Yankunytjatjara people reportedly suffered from vomiting, peeling skin, bloody diarrhoea and headaches, and more than half died shortly afterwards. Similar effects reportedly struck people of the Kupa Piti Kunga Tjuta (McClelland and others 1985). The mist appears to have been similar to the “Black Rain” reported after the Hiroshima bombing, when ash from fires effectively seeded the clouds thereby triggering rain that carried high level radioactivity to the ground, this sticky dark radioactive water staining skin, clothing and buildings, contaminating drinking water, causing acute radiation symptoms, and leaving a similar greasy dark film (Yamaguchi 2021). The Emu black mist may have included cobalt-60 (^{60}Co) from the bombs mixed with ^{59}Co from the metal firing towers. However, anecdotal reports recorded years afterwards were insufficient for modern science because no baseline demographic or Aboriginal health data were available, hence harm to humans could not be scientifically proven to the much later Royal Commission into the Australian tests (McClelland and others 1985). Adverse effects on human health further downwind from Maralinga also appear to have resulted from later testing there, more than half of the plots in the Woomera cemetery dating from the 1950s and 1960s being still-born and newly born babies and toddlers – 23 still-born and 46 other children who died around that period. An expectation of human health impacts is also implicit in the covert acquisition of human bones to be tested for ^{90}Sr, involving over 22,000 deceased Australian people, mostly infants, and almost entirely without the knowledge of their families, that was not revealed for 21 years (ARPANSA 2001). It seems hardly likely that natural biota, including cave biota, was not similarly vulnerable to direct and lingering harm from the bomb testing.

Many Australians probably assumed that all was revealed by the Royal Commission in the 1980s, but although it was successful in bringing much information into the public domain concerning past events and remaining contaminants, it also reported having been hindered and frustrated by continuing British secrecy that denied it access to important information (McClelland and others 1985). Lawyers acting on behalf of nuclear veterans seeking compensation for harm caused to themselves or their descendants caused by their exposure have since unearthed over 250,000 pages of documents to which the Royal Commission was not given access (Walker 2014, Billington 2025). Files obtained under FOI in 2011 revealed that the main burial pit had already required significant remediation work. Of 85 pits surveyed in 2010, 19 had suffered erosion or subsidence, eight required “major work” and four contained exposed asbestos (Darling 2011). Under such circumstances, it does not seem unreasonable to revisit assurances regarding conditions at Maralinga today.

Active Sites

1. North West Cape

North West Cape, a peninsula 120 km long and ~35 km wide parallel to the coastline, is one of the westernmost extremities of the Australian continent. Its spine is formed by the highly karstic Cape Range which rises to a little over 300 m altitude. The largest settlement is the town of Exmouth, located about 1100 km north of Perth and ~2000 km SW of Darwin. The Cape Range, the adjacent Ningalooo Marine Park that forms part of Australia’s longest fringing coral reef, and some surrounding coastal areas, are a UNESCO World Heritage site. North West Cape has also been an area of military activity since at least World War II. The following comments are based upon accessible literature, the author’s field observations in 1986 and 2022, and some basic first principles of karst geomorphology and hydrogeology.

The karst connection

The Cape Range karst is formed in an anticlinal ridge of Late Oligocene-mid Miocene marine limestone. The basal unit is the marly 280 m-thick Mandu Formation which crops out only in deeply incised gorges. The overlying Tulki Limestone, ~100 m thick, is widespread. The latter is in turn overlain by the 200 m-thick Trealla Limestone. These units underwent uplift in the late Miocene (Collins and others 2006) and four prominent coastal terraces of Plio-Pleistocene age reflect slower but ongoing uplift. Aeolian calcarenite has formed over parts of the terraces and lower range. While an arid environment, it is subject to significant rainfall events, typically during cyclones. The hydrogeology of the Cape Range and Ningaloo Reef are likely integrated. Cave exploration accelerated in the 1980-90s, partly due to the threat posed by a proposed major limestone quarrying and export enterprise. Several hundred caves are now known, the larger ones occurring mostly on higher parts of the range. Smaller caves at lower altitudes appear to be of flank margin origin and formed during marine high-stands (Hamilton-Smith and others 1998, White and others 2023).

The groundwater system is of Ghyben-Herzberg type, comprising a lens of fresh water floating upon denser more saline waters (Hamilton-Smith and others 1998). In theory, the differential density between fresh and saline water means that any shrinkage of the fresh groundwater lens results in a disproportionately great rise in the level of the more saline water. In reality, the fresh and saline waters are capable of some mixing. The situation beneath Cape Range involves free-draining waters higher on the range, a freshwater lens that floats upon and grades into more brackish water and a wedge of sea water at the base. Allen (1993) suggests that the water table is only ~10 m above sea level even beneath the central part of the range.

The Cape Range karst contains an extraordinarily diverse fauna that contains elements that predate the dinosaurs. The anchialine zone (where fresh and saline waters meet) contains an ancient Tethyan Sea community with a least one genus and three species not known elsewhere in the southern hemisphere (Humphreys 1983). Cape Range is a world hotspot for subterranean biodiversity including stygofauna (Humphreys 2000, 2004, 2008), and it also hosts sites of cultural heritage importance, including archaeological sites up to ~34,000 years old (Morse 1993). In the mid-1990s it was proposed that the area should be nominated for World Heritage status (Hamilton-Smith and others 1996) but resistance to this proposition was not overcome until it was eventually listed as a World Heritage Area (WHA) in June 2011.

Military activity

North West Cape is the closest base location on the Australian mainland to the South China Sea and other locations in southeast Asia that are relevant to Australia's defence. It is also close to northern Australia's principal mineral, oil and gas resources, and has the most direct all weather land supply lines from Perth and the eastern states. During World War II army contingents were posted to the area, an airfield constructed and a US submarine base established. The Exmouth Gulf area was subject to Japanese air attacks on 21 and 22 May 1942. A further raid on 16 September 1942 was the southernmost Japanese bombing during World War 2. There are two military properties enclosed within the WHA boundaries, namely the Learmonth Air Weapons Range towards the southern end of the Cape Range, used for live fire training exercises and weapons testing, and a naval communications station, principally at the tip of the Cape. The latter was established in 1967 as US Naval Communication Station North West Cape, then renamed in 1968 as Naval Communication Station Harold E. Holt. It is a joint USA/Australia facility and is probably the most powerful transmission station in the southern hemisphere. The highest of its 13 towers (387.4 m) was for many years the tallest human-made structure in the southern hemisphere (Figure 12). This base provides crucial very low frequency transmission to US, Australian and allied ships and submarines in the western Pacific and eastern Indian oceans. In addition, part of the United States Space Surveillance Network commenced operations in October 2022. Given the military importance of these facilities there is probably a high risk of this karst area coming under attack should actual conflict arise.

Environmental consequences

Adverse environmental impacts upon the karst in the Air Weapons Range area are inevitable given the nature of the activities conducted there. Detonation of explosive devices close to or on the ground surface are likely to cause rock shattering and disturbance of ground surface contours and hence rainwater infiltration patterns into the karst. Nitrogen and phosphorous compounds are released

Figure 12. Tower array at Naval Communication Station Harold E. Holt, North West Cape.

from explosives at relatively minor levels (Diaz and others 2012). Non-retrieval of unexploded ordnance (UXO) implies the possibility of other chemical agents being slowly released. Heavy metals such as zinc, copper, cadmium and lead are known contaminants of firing ranges (Barker and others 2021). Once again, it is difficult to estimate likely impacts on biota other than by analogy with human health impacts. As one extreme example, Bobonis and others (2020) have demonstrated a decrease in congenital anomalies within proximal human populations following the cessation of bombing practices in Puerto Rico.

Establishment of the town of Exmouth to support the NW Cape tracking base in 1967 resulted in considerable ground surface disturbance associated with construction of roads, houses and services for the very large number of US personnel stationed there during the Cold War years. This population influx resulted in massively increased groundwater abstraction compared to that from the few bores previously established by sparse agricultural enterprises. Water demand was further exacerbated by provision of recreational facilities that included establishment of an 18-hole golf course, bowling greens and playing grounds in this arid environment (Spate and others 1998). Although recycled water was used to establish attractive green areas, as the town developed in subsequent years, and tourism began to flourish, the "Green Oasis Syndrome" also arose, whereby efforts were made by businesses and residents to establish and maintain lush garden plant species that would not otherwise survive. The limited fresh groundwater beneath the Cape Range karst is now drawn upon at the main Exmouth borefield, by borefields established by the RAN and RAAF, and by pastoral, commercial and private parties. The local Water Corporation is cognisant and responsive to the difficulties posed by the karst, but there are also private bores in Exmouth and on Defence Lands.

In addition to the pressure on karst groundwater and its ecosystems that have been created by the water demands generated by military activities, and tourism development, the question of water quality also arises. The risk of increasing salinity due to excessive abstraction from the fresh groundwater lens is far from the only concern. As in several other parts of Australia, aqueous film-forming foam (AFFF) that contained per and polyfluoroalkyl substances (PFAS) was previously used for fire fighting and training at the tracking base. PFAS refers to a very large and very complex group of synthetic chemicals that have been used in various products since the 1950s. The chain of linked carbon and fluorine atoms is extremely strong, greatly inhibiting their degradation in the environment. The first evidence for PFAS potentially having harmful effects on humans emerged in 1955 (Nordby and others 1955) and world-wide evidence of its bioaccumulation in wildlife followed. Litigation concerning PFAS contamination proceeded in the USA during the 1990s and in 1998 the US EPA consulted with at least one PFAS manufacturer about its concerns. PFAS was identified in groundwater at three USA military sites in 2003 (Nicholson 2007). By 2010 various PFAS manufacturing plants in the USA had closed down. Consuming PFAS contaminated food or water, and breathing in PFAS, results in bioaccumulation of these very persistent substances. Likely adverse impacts upon human health include increased risk of some cancers, suppression of antibody responses and hence reduction in the capacity of the immune system to resist infections, altered metabolism and body weight regulation, and increased childhood obesity risk. The presence of PFAS in groundwater at North West Cape as a result of the use of AFFF was recognised in 2016 and environmental investigations were initiated in September 2017.

The tracking base is located on a plain at 1-20 m altitude that is formed on clay, silt, sand and gravels with sand dunes up to 20 m high to its east. This surficial material overlies an irregular and deeply weathered karstified surface formed on limestone. Groundwater is locally perched within the Quaternary sediments but is nevertheless interconnected with the karst aquifer. Of the three limestone units that exist at Cape Range, the two uppermost are highly karstic while the deepest is relatively impermeable (Allen 1993). This is facilitative of lateral spreading of solution activity, which lowering of sea level during glacial climatic stages would have encouraged.

A substantial number of shallow soil boreholes drilled as part of the PFAS investigations were unable to attain even their shallow target depth, refusal occurring due in many cases to an unidentified surface and in others to confirmed bedrock that was assumed to be limestone, generally at depths of less than 5 m (Earth Tech 2005). Tidal fluctuations were found to affect some of the monitoring stations, but with no consistent pattern of decreasing tidal influence with distance from the coast. Such irregularity would perhaps be consistent with the presence of irregularly located karstic conduits rather than evenly permeable bedrock. Groundwater flow was found to be generally directed inland, but with some localised seepage to the coast. A lack of significant contamination of fish was interpreted as indicative of sufficient dilution as to signify only a low risk to Gulf ecosystems (GHD 2018). The Defence Department concluded that the overall level of risk was low. No program to treat or remove PFAS contamination was undertaken, but a PFAS Management Area plan was developed that included provisions regarding soil and groundwater management, together with increased monitoring and review (Defence 2019). Stygofauna was not considered on the basis that it is predominantly associated with fresh water and hence more likely to occur under the adjacent Cape Range rather than the more saline water beneath the plains upon which the base is located. Stygofauna beneath the Air Weapons Range further south is nevertheless potentially at risk from contaminants from live firing and UXO decay.

Water supply has long been an issue on North West Cape, Exmouth being reliant on 34 bores with the Water Corporation having projected demand for an extra 1 billion litres by 2050. This estimate did not include supplying the increased number of personnel associated with current expansion of naval and air force facilities. The aquifer is reliant on recharge by heavy rainfall events, the future of which is in question as climate change accelerates. A desalination plant has been proposed although this may itself pose some additional environmental stresses.

2. Katherine, NT

RAAF Tindal is a permanent base facility located on karst terrane just over 300 km south of Darwin. It is sited 13 km south-east of the town of Katherine which has a population ~10,000, with ~21,000 people living in the broader region. The base directly neighbours suburbs of Katherine and allotments used for residential, rural and industrial purposes. Karstic aquifers are an important water source in this region. The base lies 9 km north-west from the Cutta Cutta Caves Nature Park and its tourist caves. The comments below are based on literature review and a brief field visit in late 2024..

The karst connection

The karst here is formed in carbonate units of the Cambrian Daly River Group, the basal unit of which is the karstic 204 m-thick Tindall Limestone. This is overlain by the siliclastic Jinduckin Formation, and then the karstic Oolloo Dolostone. Underground hydrogeological connectivity between the limestone and dolostone is believed to be precluded by the Jinduckin Formation (DLRM 2016). The Tindal karst plain is an exhumed pre-Cretaceous palaeokarst surface that formed under different topographical and hydrological conditions to those at present. The caves exhibit strong palaeokarst inheritance and present day drainage through the karst is dictated by palaeokarst structures that are contrary to what might be anticipated from the present day land surface contours. Convection cupolas in the Cutta Cutta caves indicate a degree of cave formation by thermally-heated waters (Lauritzen and Karp 1993). Hence subsurface drainage patterns are even less predictable from surface appearances than is already the case with conventional karst.

This karst forms part of the very extensive Cambrian Limestone Aquifer (CLA) that spans three major sedimentary basins, the Daly, Georgina and Wiso, in each of which the limestone is named differently despite their all being the same unit. The Georgina and Wiso drain northwards over basement highs into the Daly (Currell and Ndehedehe 2022). The presence of similar subterranean crustaceans across hundreds of kilometres highlights the connectivity of aquifers beyond Katherine to the Beetaloo area, where proposals for fracking have provoked considerable controversy (Rees and others 2020). The Daly is one of few rivers in the Northern Territory that maintain significant flow throughout the dry season, the vast majority of this coming from karstic and fractured aquifers, mostly formed in Tindall Limestone and Oolloo Dolostone (Tickell and others 2002). The karst groundwater is an important resource, being used for residential, rural, industrial and other commercial purposes, including irrigation. It is obtained by means of bores and surface interception downstream of outflows. These karst waters are also an important recreational resource for swimming, boating and fishing. Bathing in warm karst spring waters is an important part of the agenda for many tourists. Because Aboriginal people construe bodies of water spiritually, socially and jurally, rather than just as physical phenomena, the karstic groundwater is deeply significant to them (Langton 2006, Jackson and others 2023).

Military activities

On 2 April 1942 the then-Katherine airfield was bombed by Japanese aircraft during the most inland of the bombing raids to which Australia was subject during World War II (Coulthard-Clark 2001). The origins of the present air base date from 1942 when it was constructed by the US 43rd Engineer Regiment in preparation for use by a squadron of B24 Liberator bombers that was never actually deployed due to changes in the pattern of Japanese military activity. Originally known as Carsons Field the present base was renamed after World War II as Tindal. Between 1963 and 1970 it was restored as a “bare base” to back-up Darwin. It was redeveloped from 1984 as a permanent base to station RAAF aircraft. Subsequent development has included infrastructural improvements, enlargement and strengthening of the runway, and the establishment of additional hardstand areas for parking aircraft. It is currently being further developed. The base complex extends over 122 km^2.

Environmental consequences

Construction and progressive development of the base has entailed land clearing and landscape modification by both excavation and filling, including the filling of sinkholes. This has changed surface contours, and extensive areas have been rendered impermeable by sealing of the airfield and aprons. Drainage derangements have included construction of a drain from the base fire station to a nearby wetland area. These various actions have collectively deranged the natural patterns of rainfall and floodwater infiltration into the karst. Land surface stability associated with sinkhole development is a known issue in this karst area, as is the potential for dispersal of water-borne contaminants through the subsurface karst and towards the Katherine River (Karp 2002, Tickell 2005, Kruse and Munson 2013). Water use has increased in this part of the karst due to operation of the base. Other implications of base operations include those associated with training activities and various risks in relation to the storage of substances potentially injurious to the karst. Existence of the base also implies the risk of substantial further damage to the karst should the base be targeted in the event of actual conflict. Training in fire suppression again involved the deployment of PFAS, and of combustion products used to ignite fires for training purposes.

The Defence Department used PFAS for fire-fighting and training at Tindal for a decade up to about 2004. Following recognition of PFAS contamination at some of its sites in November 2016, including at Tindal, Defence informed local residents of the hazards posed by contamination of groundwater and local streams. Because PFAS can enter the human bloodstream through drinking contaminated water, consuming food produced using contaminated water for irrigation including vegetables and meat, or inhaling contaminated dust, an advisory was issued in December 2017. It warned against drinking bore water, eating food products potentially contaminated by it, or swimming in it. Residents were advised not to eat seafood, or consume home produce such as eggs, fruit or leafy greens. After investigation of the base and surrounds, it was revealed in 2018 that PFAS, primarily from the base fire station and fire training area, had entered the groundwater and had migrated towards the Katherine River, contaminating both bore water supplies and the Katherine town water supply (Figure 13). Analyses of locally caught barramundi showed PFAS levels up to six times above safe levels, cod and catfish up to 17 times safe levels, and some other fish species up to 70 times.

Defence installed rainwater tanks on properties previously reliant on bore water, but questions arose as to whether these would be filled on an ongoing

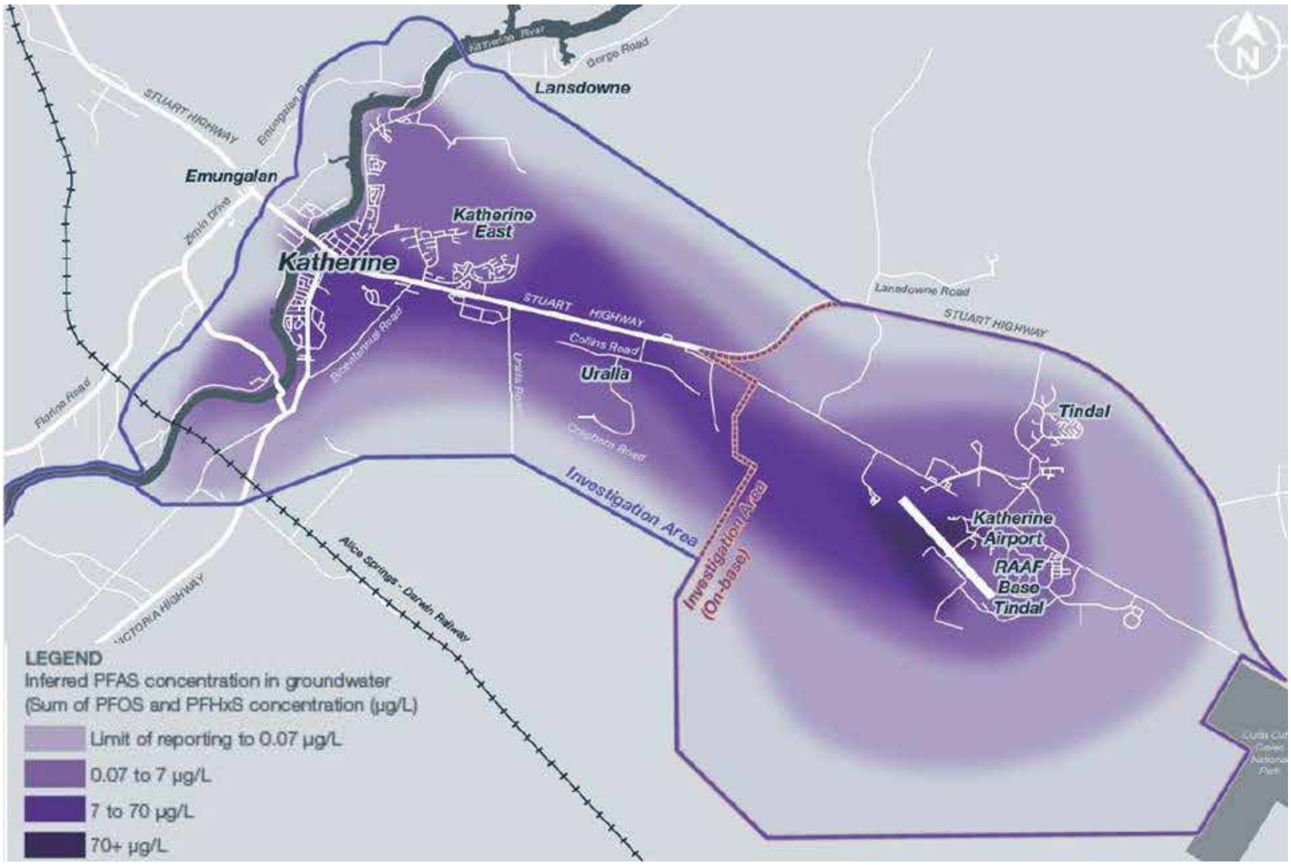

Figure 13. PFAS plume in karst groundwater at Katherine. From O'Brien and Edwards (2019)

basis in the event of droughts. Class action was launched by multiple parties seeking compensation on the basis of health risks, the inability to continue to use the water, and diminished property values. Despite evidence from overseas, Australian health authorities continued to assert that any hazard PFAS posed for human health remained unproven, and the Defence Department resisted performing blood tests on humans. The litigants alleged negligent behaviour and negligent failure to inform on the part of the Commonwealth, on the basis of it being reasonably foreseeable that waters, liquids and soluble materials used at the base would get into the water. It was alleged that the Commonwealth had known PFAS was harmful since 1987 but had said nothing, and that some purchasers had unknowingly acquired contaminated properties after that time. It was further argued that the Commonwealth's actions were contrary to Northern Territory water legislation with which it was obliged to comply under its own *Commonwealth Places (Application of Laws) Act 1970*, and were also in breach of section 28 of the *Environment Protection and Biodiversity Conservation Act 1999*, the latter requiring that no Commonwealth agency may take action that will have, or is likely to have, a significant detrimental impact on the environment. One class action for residents of Katherine and two other Defence sites was settled for $215.5 million in 2020, and another for various Defence sites was settled for $132.7 million in 2023.

A new filtration plant developed by the Defence Department and the NT water corporation, which is capable of filtering 28 monitored PFAS compounds, commenced operations in 2023. The winning of some compensation has not entirely resolved the health concerns of some local residents who were previously exposed or are still suffering disadvantage. Nor can it remediate the persistent environmental damage inflicted upon this karst. Issues that remain concerning continued operation of the base include such things as the potential for accidents involving hazardous substances stored on site. The potential also remains for this karst to be further injured should the base be subject to attack in the event of actual conflict.

Discussion and conclusions

Australia has not been immune from the serious environmental damage that military activities can inflict on karst areas. Legacies of past practices include damage to surface landforms, derangement of drainage causing interference with infiltration of meteoric waters and contamination of karst aquifers that cannot be remediated. These impacts have arisen largely because the nature and sensitivity of karst environments was not recognised at the time these activities were initiated or undertaken, and/or because military objectives were prioritised to the extent that all other considerations were effectively ignored, as in the Montebello Islands and at Maralinga. However, the fact that military activities continue in some karst areas such as North West Cape and Katherine means that the issue is not just one of regrettable legacies from ignorant times past but also involves the need for careful ongoing karst environmental stewardship. The scale of investment effectively precludes relocating major facilities such as the bases at North West Cape and Katherine to less sensitive, non-karst sites, but the very highest level of environmental management is needed there. Further military facilities should not be sited on or proximal to karst.

The situation at Katherine particularly highlights management of hazardous materials as one concerning facet of environmental management on and around Australia's military bases sited on karst. The *Stockholm Convention on Persistent Organic Pollutants* (POPs) is a global treaty aimed at protecting human health and the environment from harmful chemicals that persist in the environment. In fulfilment of its obligations as a signatory, the Australian government has now banned the importation, manufacture and use of the more prominent varieties of PFAS, effective from 1 July 2025. However, we may not have heard the last of PFAS with advent of the new Australian government ban, because PFAS have a wide range of military applications beyond the fire-fighting foams that have already proven problematic. They are utilised in munitions to improve performance and durability, increase shelf life and reduce the likelihood of unwanted explosions due to shock. PFAS represents from 1 to 3% of the net explosive weight of about 20% of all common US weapons. PFAS are used as a binder in conventional and strategic weapons platforms and in aircraft and various missile systems. Hence, environmental risks are posed by firing and disposal of munitions and by the burning of some military waste (Cottrell 2025). PFAS are also found in sealants, cleaning fluids, waterproofing agents, refrigerants, electronics, batteries and protective clothing. While the Australian ban on PFAS is consistent with its obligations as a signatory to the Stockholm Convention, that convention also makes provision for exemptions for defence purposes. Moreover, arbitrary exemptions from laws can also occur at various levels. In March 2025 it was revealed that a $270 million fuel tank facility to support US operations at Tindal and elsewhere (Project Caymus) had been built at Darwin by a contractor without having first obtained the permit required under the *Northern Territory Building Act 1993*. The 11 large fuel tanks, to hold 300 million litres, had been due for completion in 2023 but were still not operational due to water intrusion into the leakage detection system. The Northern Territory Chief Minister, whose government enthusiastically encourages any development perceived as being financially beneficial to Darwin, indicated that no penalty would be applied (Hislop and O'Shea 2025).

Considerable further research is required to better understand the nature, extent and longevity of military impacts on karst in Australia, and indeed elsewhere. Many questions remain concerning the distribution and persistence of radioactive products from the Montebello and Maralinga nuclear tests. The extent to which transmission of radioactive contaminants via karstic groundwater, as has occurred with the PFAS at Katherine and North West Cape, is one obvious example. Such investigation of lingering radioactivity as has occurred at Maralinga to date has been confined to surface and near surface studies rather than groundwater investigations. Ascertaining whether the elevated uranium levels upwind of the Maralinga test sites at Carle Thuka (Lake Maurice) is explicable by natural erosion of uranium from granites further north, or is instead due to redistribution of fallout from the bomb testing via groundwater, warrants examination. Ascertaining whether the Carle Thuka lake basin hosts concentrations of any other non-natural radionuclides such as ^{137}Cs might offer one possible avenue for resolving the question. This isotope has been produced only by nuclear weapons testing and has been distributed globally to the extent that it can be used as a marker horizon in soil erosion studies, including in Australia (Loughran and others 1992). Any particular concentration of ^{137}Cs at Carle Thulka might be suggestive of its transmission by water from the Maralinga test area. Greater confidence may be achievable by more detailed studies to determine the age of non-natural isotopes present, perhaps along the lines of work by Stäger and others (2023) who were able to discriminate between "older" ^{137}Cs from weapons testing fallout and "younger" fallout from the Chornobyl fallout disaster based on $^{135}Cs/^{137}Cs$ ratios in wild boar meat samples. Similarly, the possibility of a plume into the karstic aquifer beneath Montebello Islands and into the sea warrants investigation. The Katherine experience should mark the end of military environmental assessments that ignore what is hidden beneath our feet. A lack of baseline data typically complicates assessment of impacts on biota. One possibility worth exploring may be whether any dateable bone or other organic deposits that may allow insight into pre versus post impact populations exist in caves on the Montebellos, in crevices or blowholes at or near Tietkens Plains, or around the bases at North West Cape and Katherine.

The case studies presented in this paper represent only part of the story concerning military impacts on Australian karst. Other areas of karstic or potentially karstic terrane that have been subject to military impact occur around Lancelin in Western Australia and possibly near Murray Bridge in South Australia. The Australian Government has recently acquired land in North Queensland on which to establish its new Greenvale Training Area, consistent with the Australia-Singapore Military Training Initiative. This will cater for up to 14,000 Singaporean Armed Forces personnel involved in live firing and other operations. The site is not far from the Broken River karst from where recent remains of the Ghost Bat have been recorded, and hence operations there might conceivably impact upon this threatened species.

Less conspicuous potential military impacts on karst include the winning of construction materials such as cement, and air pollution. Climate change triggered by the massive scale and geographic spread of atmospheric emissions from military sources can have implications for karst far distant from any operational sites, through such mechanisms as changes in precipitation volume, type or seasonality, and hence infiltration and runoff, and also biotic changes that influence water chemistry (Viles 2003, Morrisey and others 2021). Most military CO_2 emissions result from the use of liquid fuel by aircraft. If global military $C0_2$ emissions were amalgamated as if the output of a single country, it would rank fourth behind China, the USA and India (Parkinson 2023). It seems ironic that many military organisations and governments now recognise anthropogenic climate change as having very significant national security implications, yet they seek to quarantine their own military emissions from climate change discussions and protocols (Crawford 2019). Even though its military is the world's largest institutional consumer of hydrocarbons, the USA government insisted upon an exemption for military emissions before it would sign the 1997 Kyoto Protocol (Neimark and others 2020).

As an Annex 1 country under the Kyoto Protocol, Australia is obligated to set binding emissions reduction targets through the United Nations Framework Convention on Climate Change (UNFCC). The guidelines produced by the Intergovernmental Panel on Climate Change (IPCC) require that military fuel use should be reported under IPCC category 1.A.5, which includes all mobile fuel (i.e. fuel used by planes, ships and ground transport) and all stationary fuel consumption (i.e. used on bases). The most disaggregated level should be provided for each source, but aggregation is permitted to protect military information, which stymies differentiation of mobile from stationary emissions, a particular concern at a time when military conflict and expansion of facilities, production and procurement of war materiel, and active field testing and training are all increasing markedly (Alexander 2025). Accounting is further stymied by the failure of some states to submit their data or their submission of incomplete data, and Australia is one of the culprits (Military Emissions Gap 2025). However, CO_2 is not the end of the story. Release of nitrogen oxides, vapour trails and cloud formation due to aircraft contributes nearly twice that of their CO_2 emissions to global warming (European Commission 2020).

A complete accounting of military impacts on Australian karst would also need to include the wider Australian defence industry which includes numerous non-governmental organisations that supply equipment, services and weapons to both the Australian Department of Defence and for export, the latter potentially also causing environmental detriment to those overseas places where they are used, stored or otherwise disposed of. Estimates of the size of this wider Australian defence industry differ because arbitrary boundaries have to be selected where companies also service a civilian market and produce both military and civilian goods. A broad impression can be gleaned from approximately 61,600 people having been employed in the Australian defence industry in 2021-22 and the Australian government having awarded over $38 billion in contracts in 2022-23. If supply chain and supporting businesses are factored in, over 100,000 jobs are involved (Australian Government 2024). In 2018 Australia was the world's 20th largest exporter of military products and the Gillard ALP government initiated a program aimed at increasing this ranking to 10th largest exporter. Many of the businesses involved in the Australian defence industry are of small to medium size and they occur in scattered locations across the country. The extent to which any may be located in karst areas, obtain their resources directly or indirectly from karst areas, or otherwise impact karst areas, has never been evaluated. While the Department of Defence may now undertake environmental evaluations and strive to adapt to environmental laws, the same is not necessarily the case for its suppliers or exporters.

Massive environmental harm is likely to be inflicted upon karst systems if bases or non-government defence industry sites located in karst areas should come under attack in the event of actual conflict occurring on our shores. Modern explosive ordinance is likely to result in major landscape destruction by craterisation. The surficial sediments at North West Cape and Katherine are generally thinner than the depth of some bomb craters produced by conventional weapons even back in the 1970s (Kiernan 2013). This implies that any filtering of the water being transmitted downwards into the karst is likely to be eliminated. Destruction of previously productive soil profiles and contamination with toxic materials in munitions or other weapons, or leaking from targeted facilities, also has implications for biota, including cave fauna that is commonly highly sensitive to environmental disturbance. Australia has thus far been fortunate in not having active modern conflict in any part of its karst estate, and those militarily-inflicted harms to which Australia's karstlands have been subject due to military impacts have been inadvertently inflicted in pursuance of sufficient deterrent capability to ensure this fortunate situation continues.

However, the Australian government is currently spending $800 million to transform the Learmonth air base from a bare base to a battle-ready facility. The US military wishes to establish its own jet fuel storage at Learmonth of 500,000 barrels, some 40 times greater than is contained in the current Australian fuel farm. The Learmonth expansion is part of an $18 billion upgrading of bases across northern Australia, which also includes major expansion of the Tindal facility on the Katherine karst. Tindal is currently being upgraded to facilitate its stationing of six nuclear capable US bombers as part of defence agreements entered into by previous Australian governments (Figure 14), thereby increasing the likelihood of this karst being subject to attack and contamination should actual conflict arise in the future. Both North-West Cape and Tindal are likely to be prime targets, potentially nuclear targets, in the event of conflict between the USA and China. Given that international protocols aimed at reducing harm to environmental and heritage values during armed conflict are specifically nullified if military facilities are sited in the same locations, Australia's karst environments should not be put at any further risk than they already face by the establishment of any additional military or wider defence industry facilities within or proximal to them.

Figure 14. Tindal base in the Katherine karst is currently being upgraded for stationing of nuclear-capable US bombers.

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