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Fascinating succulents

The plant life found in the world's deserts includes a remarkable array of diverse species—including cacti, agaves, desert shrubs, and hardy grasses—that have evolved to flourish in extremely arid environments. These resilient plants often possess specialized adaptations, such as succulent foliage or extensive root systems.

The Succulent Karoo ecoregion, stretching from southwest Namibia down into South Africa, encompasses the arid region of Namaqualand, which is home to the world's most diverse desert flora. The distinctive characteristic of Namaqualand is the predominance of dwarf shrubs with succulent leaves. Typical species are members of the Aizoaceae family (the lithops and mesembs, or vygies), but *Crassula*, *Haworthia*, and other genera are also important. Some 1,700 species of leaf succulents grow in the Succulent Karoo, of which 700 are contracted, dwarf forms. Namaqualand has between four to six times the plant diversity of equivalent-sized areas found in other foggy, winter-rainfall deserts across the world, such as Mexico's northwestern Baja California, Chile's southern Atacama, and Morocco's southern coastline.

Lithops optica is one such succulent of the family Aizoaceae and these plants are often referred to as "living stones"; their scientific name is derived from the Greek *lithos*, meaning "stone," and *opsis*, meaning "appearance," due to their remarkable resemblance to the pebbles found throughout their natural environment. *L. optica* is endemic to the area around Lüderitz, in the southern Namib Desert, and found nowhere else on Earth. It thrives in its unique habitat, which primarily consists

▼ **Desert icon** *Standing tall amid Namibia's arid landscape, the iconic quiver tree is a good example of adaptation to the harsh desert environment.*

PLANT POACHING

Plant poaching, driven by human greed and the desire to possess rare specimens, is becoming an increasingly alarming issue, and Namaqualand, with its rich biodiversity and endemic plants, has become a prime target. Operating under the guise of tourists, ruthless environmental criminals deplete the region's plant resources. The specimens they smuggle out of the region often perish during transportation, introduce plant pathogens, and disrupt the delicate ecological balance. Ultimately, poachers prioritize profit over environmental preservation, disregarding the well-being of the ecosystems they exploit.

of coastal plains with sandy terrain, and rainfall averaging between only 0.8–2 inches (20–50 mm) per year, with frequent fog. Among rocks and gravel, these plants can be challenging to detect, due to their exceptional camouflage. Their flowers open only in the late afternoon, closing again at dusk, and they can be pollinated by the bees, flies, wasps, gnats, and so on that are common in the area. *Lithops* are self-sterile, so cross-pollination is critical for survival.

Aloidendron dichotomum—previously *Aloe dichotoma*, and commonly known as the quiver tree—is a unique and iconic succulent plant found in Namaqualand and other arid regions of southern Africa. It possesses a distinctive appearance, featuring a thick trunk that branches out into multiple symmetrically oriented stems. Its branches are adorned with densely packed succulent leaves, creating a striking crownlike look. The quiver tree has evolved to thrive in harsh desert conditions, utilizing its succulent leaves to store water during prolonged droughts. Within the local ecosystem, where few other tree species exist, it serves a vital role by offering shelter to various desert-dwelling creatures. The San people have historically used different parts of the tree for practical purposes, notably hollowing out its branches to fashion quivers (arrow holders) for hunting—hence its common name. Today, the quiver tree is a symbol of strength and beauty in the arid landscapes of southern Africa.

▲ **Camouflaged *Lithops***
(top) A Lithops *species consists of a two-lobed fused and thickened pair of opposite leaves with a very smooth texture and a very short stem that is not visible. (bottom) Succulent* Lithops *species are well adapted to survive in the desert and also difficult to spot by herbivores because they are camouflaged to resemble the pebbles of the environment.*

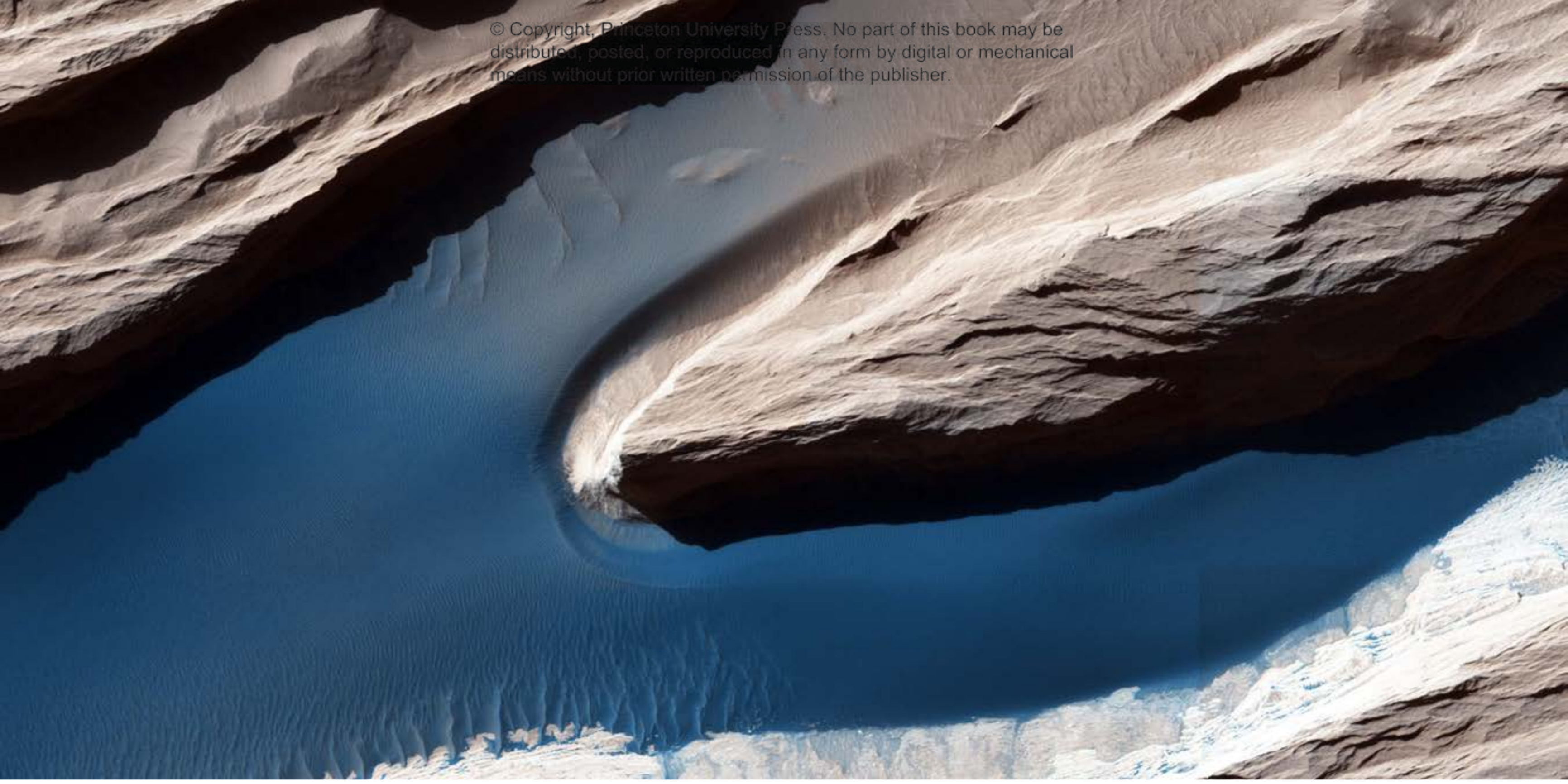
Beyond Earth: deserts of the universe

If moisture deficits define aridity (on Earth), then the absence of moisture on other terrestrial bodies in our solar system suggests that desertlike conditions could, even should, be present in their landscapes. And to some degree this is the case, though marked differences compared to Earth in surface temperatures, and in atmospheric densities and compositions, make direct comparisons with our deserts—and expectations of what features might be found, or formative processes experienced—rather challenging.

When the first astronaut set foot on our Moon in 1969, his footfall generated puffs of dust that indicated a surface that was not simply solid, but mantled by soft, mobile sediment. The growth of extraterrestrial exploration (via multiyear, even multidecadal, unmanned spacecraft missions that have reached, orbited, observed, and returned data from planetary bodies to Earth) is providing a wealth of data on other landscapes in our solar system. Dunes have been identified on three other planets (Mars, Venus, and, more recently, Pluto) and on one of Saturn's moons, Titan, while massive dust storms have been observed across the surface of Mars and Titan. Even alluvial fans are observed on Mars—evidence, along with possible channel systems, of the presence of water in the past. Remotely controlled rover vehicles have also been landed on the surfaces of both the Moon and Mars and successfully utilized in exploration, providing images akin to those we have of Earth's deserts, as well as carrying out simple experiments on the sediments and features they have encountered.

Planets and moons have to have atmospheres in order for sediment-moving winds to blow from high-pressure to low-pressure areas. For there to be sediment to move in the first place requires rock breakdown via weathering, which in turn calls for significant temperature differences or some form of salt crystallization to force

Red storm
In June 2018, a dust storm developed on Mars that eventually engulfed the planet's entire surface. NASA's Curiosity Rover vehicle, which has operated continuously in Mars' Gale Crater since August 2012, recorded the early stages of the storm that lasted over three days.



particles apart. Planetary scientists tend therefore to consider "aridity" in the sense we understand it with reference to Earth to best apply to other bodies that first have a solid surface (thereby excluding gas bodies such as Jupiter) and second have atmospheres containing condensable gases (such as methane on Titan).

Mars, the cold red planet, 50 million miles (80 million km) farther away from the Sun than Earth, has experienced significant climate changes, including stages when liquid water was present—which may explain the presence of channel-like landforms in some regions. Today its thin carbon dioxide (CO_2)-dominated atmosphere is conducive to the movement of sediment by wind, the most prevalent environmental process affecting its surface. There are many spectacular dune fields, and other areas showing the efficacy of wind erosion, where moving dust and sand have sculpted large fluted hills and faceted the surfaces of exposed pebbles and rocks into ventifact forms.

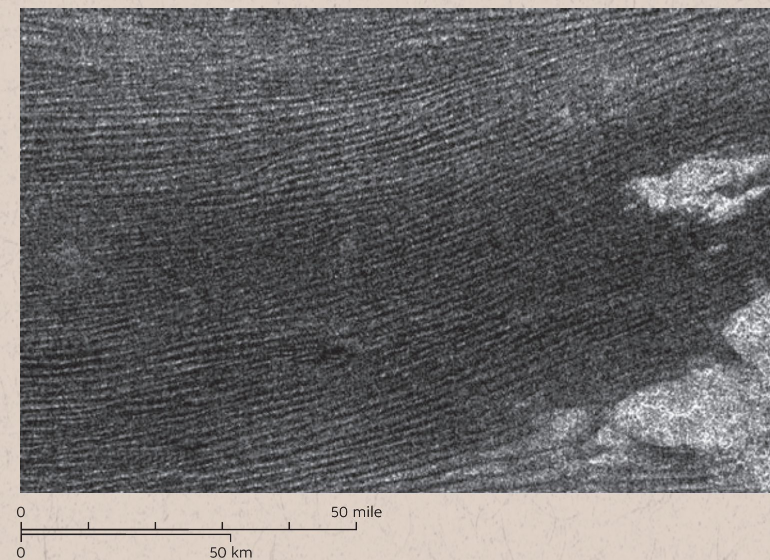
Though a moon of Saturn, Titan is larger than the planet Mercury. It has a dense, extremely cold (average temperature -292 °F/ -180 °C) atmosphere of methane. This can condense into a liquid and fall as rain, explaining the occurrence of fluvial-like landforms and lakes on the moon's surface. Strong winds also allow aeolian processes to operate, with multiple fly-pasts by the Saturn-exploring NASA *Cassini* spacecraft from 2004 to 2017 revealing fields of equatorial linear sand dunes comparable in morphology to those of the deserts of southern Africa and Australia.

The most recent discovery of arid landscape features has been on the surface of small, distant Pluto, which, depending on orbital position, is between 2.66 and 4.67 billion miles (4.28–7.5 billion km) from Earth, and only a sixth its diameter. NASA's New Horizons mission flew by Pluto in 2015, producing imagery that shows its thin, nitrogen-dominated atmosphere possesses winds that have formed the distinctive Sputnik Planitia dune field—made not of sand but of frozen methane particles deposited on the surface of one of the planet's extensive ice plains.

▲ **Martian winds**
Wind is one of the most active forces shaping Mars' surface in today's climate. Wind-carved features such as these, called "yardangs," are common on the Red Planet. Wind has also deposited fine sand on the floor of shallow channels between the yardangs. On the sand, the wind forms ripples and small dunes. In Mars' thin atmosphere, light is not scattered much, so the shadows cast by the yardangs are sharp and dark.

PLANETARY DUNES

Dunes on other planets come in all sorts of patterns, forms, and materials. Many forms are similar to dunes on Earth: for example, in the Belet dune field on the equator of Saturn's moon Titan, linear dunes extend east–west over tens of miles, spaced about 1.2 miles (2 km) apart, captured here in a radar image from the *Cassini* spacecraft. On Mars, we have the benefit of dune images not only from space but captured on the surface by the Curiosity Rover. For example, "barchanlike" dunes have been recorded in high resolution from NASA's *Mars Reconnaissance Orbiter*, in this example (farthest right) in 2015, showing ripples on the dune's upwind side as the dune migrates over a fractured rocky surface (from the top-right corner of the image toward the bottom left). The amazing Curiosity image of another barchan form, the so-called Namib dune in the Bagnold dune field (named in honor of one of Earth's most spectacular dune fields and, in turn, one of dune science's earliest proponents, Ralph Bagnold), shows the downwind slip face of the dune, again in 2015. This is about 13 feet (4 m) high, and displays the typical patterns of sediment avalanches that form as a dune moves forward. Repeat analyses suggest that this dune is migrating at a rate of about 3 feet (1 m) per Earth year. The upwind, or lee, sides of the dunes are covered in ripples, shown in close up in another Curiosity mosaic image, from the Bagnold dune field. Elsewhere on Mars, dunes that do not have an earthly analogue are found.



▲ **Titan dunes**
The Belet dunefield on Titan.

▶ **Barchan**
A classic barchan dune on Mars.

▼ **Martian dune**
Curiosity Rover image of the slip face of the "Namib dune" on Mars.

[redacted]

2

Why are there deserts on Earth?

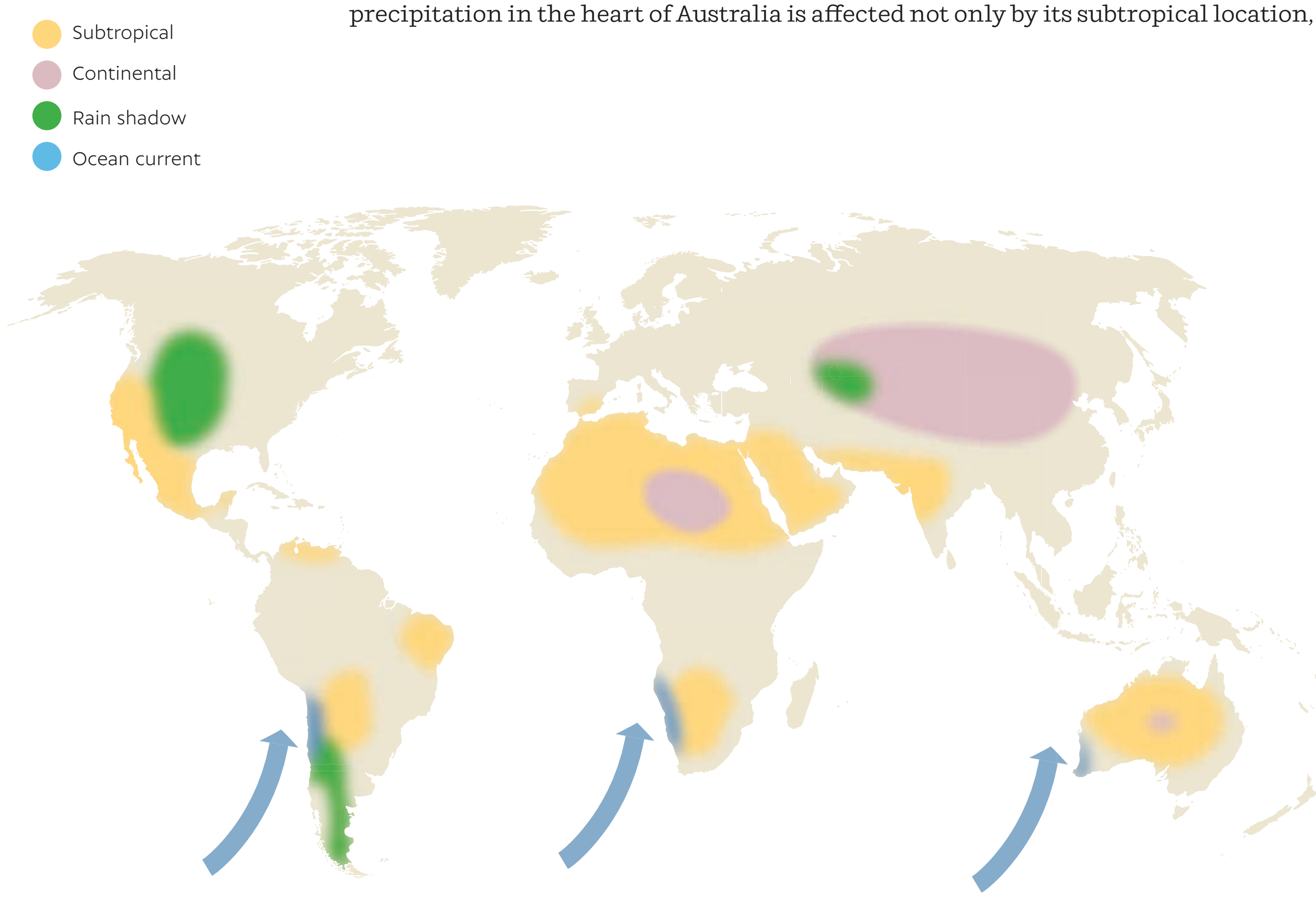
What causes dryness, and where?

It is possible to break down the atmospheric and environmental factors that cause the moisture deficits around the globe into four broad influences: atmospheric stability; distance from the ocean (or "continentality"); topographic ("rain shadow") effects; and the influence of cold ocean currents on neighboring coastal areas.

Dryness drivers
The generalized main causes of aridity in the world's desert and dryland areas.

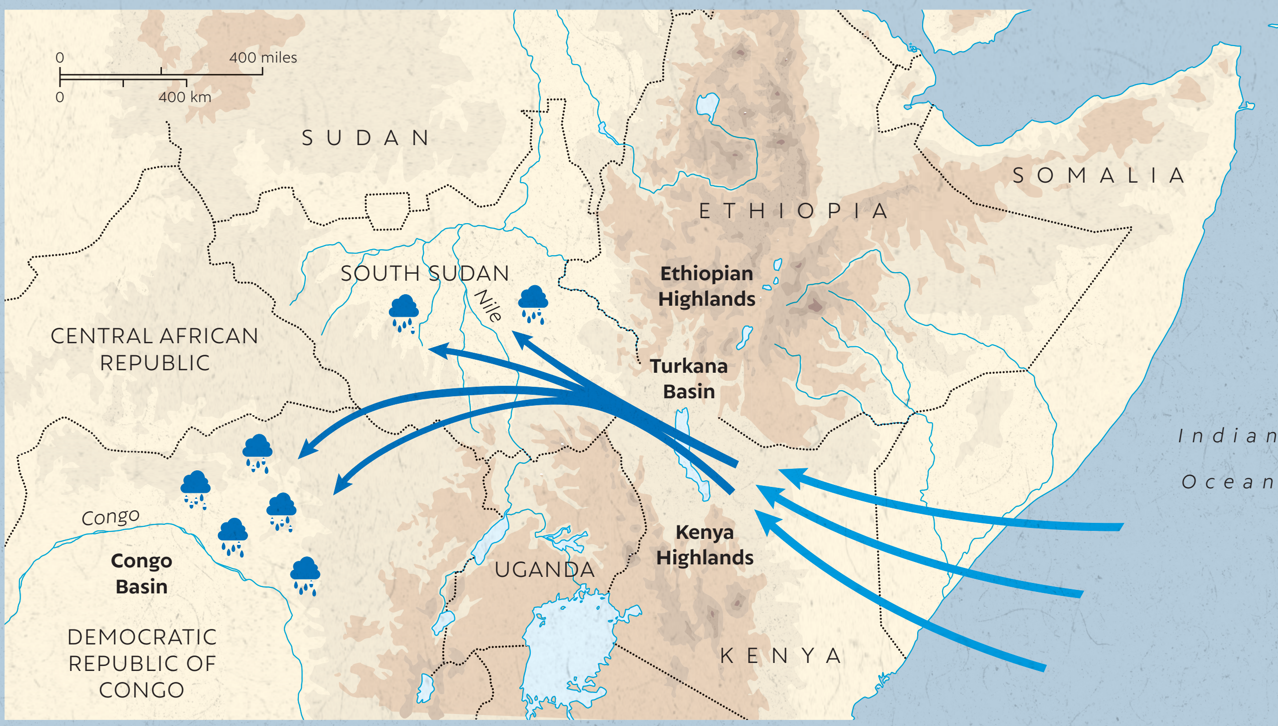
Every desert and dryland area on Earth is caused by at least one of these factors. The great belts of subtropical deserts, including the Sahara, Arabian, and Thar Deserts of the northern hemisphere, and the Kalahari and Australian Deserts of the southern, result from atmospheric stability that limits rainfall. The extensive deserts of central Asia and China are largely caused by their great distance from the oceans. Desert areas also occur on the lee (downwind) side of mountain barriers, creating dynamic deserts and drylands, particularly in North and South America. Finally, on a much smaller scale than any other mechanism, cold ocean currents cause dryness on the western Atlantic coast of southern Africa, parts of the Pacific coastlines of South and North America, and, to a lesser extent, the west coast of Australia. While the areas affected by this final influence are relatively small, the processes involved have contributed to the existence of two of the driest deserts on Earth: the Namib and Atacama.

Each of these mechanisms results in limited moisture in the atmosphere over the land, and therefore to little precipitation. To compound matters, some individual desert areas are influenced by more than one of these factors. For example, low precipitation in the heart of Australia is affected not only by its subtropical location,



RIVER IN THE SKY

Scientists have often wondered why tropical East Africa, spanning South Sudan, Ethiopia, and Kenya, is dryland—its latitude means it ought to be a wetter region, like the Congo Basin to the west. Research in 2023 by Callum Munday and colleagues has shown that the answer seems to lie in the effect of the east–west Turkana Basin, a gap between the Ethiopian and Kenya Highlands created by faulting in the East African Rift. This channels low-level winds from the Indian Ocean as the "Turkana Jet," carrying water vapor away from eastern Africa toward the Congo, drying the former and making the latter even rainier than it would otherwise be.



but by distance from the ocean, while the eastern Australian interior is also impacted by the north-south Great Dividing Range inhibiting rain-bearing easterly trade winds reaching farther inland. Taken together, almost 75 percent of Australia is consequently either arid or semiarid.

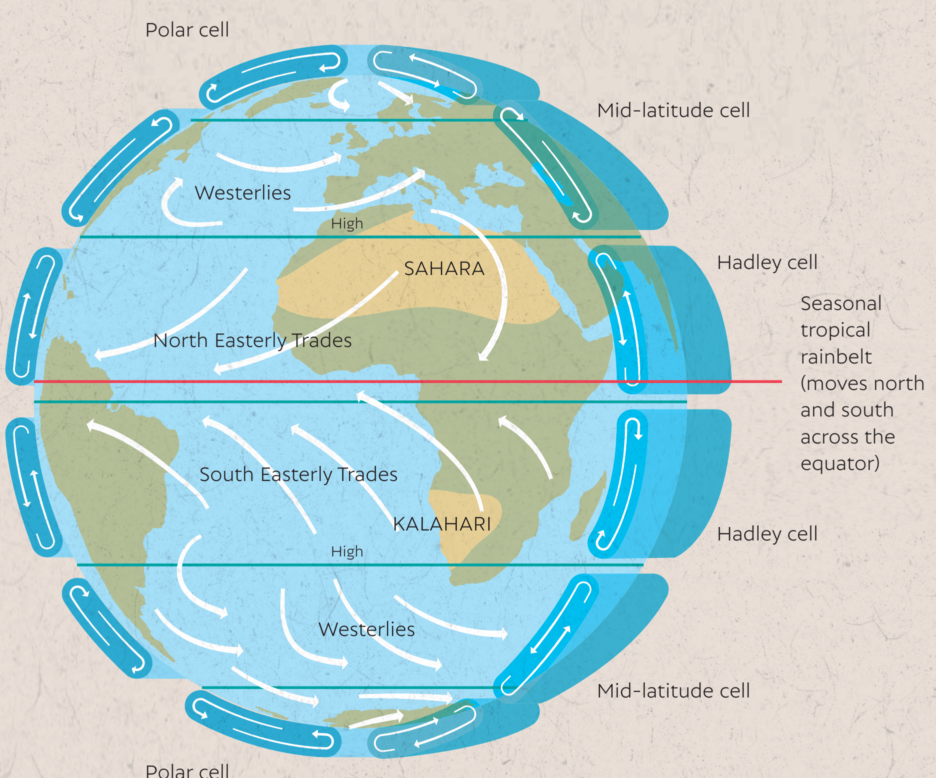
Land masses are not equally distributed over the Earth's surface, with 68 percent found in the northern hemisphere. When combined with the occurrence of the atmospheric and environmental factors that cause deserts and drylands, the size of landmasses as well as their latitudinal distributions result in each of Africa and Asia possessing over 30 percent of global arid lands, with 12 percent in North America, around 5 percent in southern Europe, just 9 percent in South America, and 11 percent of the global total in Australia.

Atmospheric stability: subtropical deserts and savannas

The subtropics, centered on latitudes 30° North and 30° South, are the location of great atmospheric belts of moisture-limited stable air. Atmospheric stability tends to bring dryness, creating the major desert and dryland zones of Afro-Asia that include the Sahara, Arabian, Lut, and Thar Deserts; the Sonoran and Chihuahuan Deserts of North America; and the large, dry expanses of the Kalahari and Australia in the southern hemisphere.

Dry descent

Many subtropical deserts and drylands, such as the Sahara and Kalahari in Africa, sit under the dry descending air of the atmospheric Hadley cells. The diagram below shows the general position of the Earth's circulation cells and the associated surface winds.



These stable air masses represent the descending limbs of large circulation cells that originate in the wet tropics (the Hadley cell) and the mid-latitudes. Descending air is generally moisture-depleted, creating stable conditions in the lower atmosphere, and surface trade winds that blow out of the driest areas, further limiting rainfall incursion and contributing to evaporative loss. The resulting dry conditions tend to comprise central arid regions, with surrounding semiarid and dry-subhumid areas that are affected seasonally by elements of the monsoon rains of the tropics or the westerly depressions of the mid-latitudes.

Given their subtropical location, many of these deserts and drylands are hot all year round (mean temperatures of the warmest months exceeding 86 °F [30 °C]), such as in the central Sahara and Arabia, or they have hot summers and mild winters (mean

▼ **Subtropical Arabia**
The desert dunes of the Arabian Peninsula, here in the United Arab Emirates, are influenced by the aridity caused by dry descending subtropical air.

Cerrado
Located between the Amazon Basin and Pantanal wetlands, this extensive savanna area covers over 7.5 million square miles (2 million sq km) of Brazil.

Desert dates
The oasis at Tafilalt, Morocco, sits on the northern margin of the subtropical Sahara Desert.

coolest month temperatures in the 50–85 °F [10–30 °C] range), for example in the southern Sahara, the Kalahari, and the deserts of Mexico. These expansive deserts include depositional sedimentary basins that have some of the most extensive areas of sand dunes on Earth.

The aridity gradient of subtropical drylands results in a transition from almost vegetation-free conditions to surrounding better-vegetated areas, sometimes called semideserts. These have a distinct climatic seasonality, expressed not so much in temperature variations as in the distinct timing of rainfall. On the equatorial side of subtropical drylands, vegetated areas comprise savanna grasslands and dry tropical woodlands, the result of a commonly short, hot, summer rainy season and dry winter months, which aggregate to give a net mean annual moisture deficit.

Some subtropical savanna areas occur without an associated desert core—notably the Cerrado (Portuguese for “savanna”) and neighboring Caatinga (dry, thorny shrubland) regions of central-eastern Brazil. Other subtropical drylands also have, on their temperate (mid-latitude-facing) margins, conditions with a reverse seasonality of wet winter months and hot, dry summers. These include so-called Mediterranean climates, among which are the semiarid to dry-subhumid drylands of the extreme north of Africa, the Levant, and southern Europe, as well as occurring in southeastern and southwestern Australia and South Africa’s Cape region.

Deserts and drylands of the continental interiors

Continentality, or distance from the ocean, is an important contributor to moisture deficits in the interior of the largest land masses. Continentality is responsible for the great desert areas of central Asia centered on latitude 45° North, and the dry regions of central North America, as well as acting as an additional contributor to aridity in the heart of the Sahara and Australia.

▼ **Gobi Bactrian**
This camel species native to the Gobi Desert, Mongolia, is well adapted to the continental desert climate.

Rain-bearing winds, such as the tropical monsoons and temperate-region westerly depressions, derive most of their moisture from the oceans. Precipitation on land generally therefore decreases in an inland direction from the coast.

Asia

The belt of mid- and higher-latitude drylands that stretches from the Caspian Sea in Turkmenistan in the east, to Mongolia and China in the west, is a function of continentality, with the Dzoosotoyn (Gurbantünggüt) Desert, in the China-Kazakhstan borderlands, up to 1,644 miles (2,645 km) from the nearest ocean, being the most continental place on Earth. Other major deserts of continental Asia include the Gobi ("waterless place") in Mongolia and China, the Taklamakan Desert of China, and the Karakum Desert of Turkmenistan. The Taklamakan and Gobi Deserts also sit at relatively high altitudes, ranging 2,900–5,000 feet (900–1,500 m) above sea level, which, when combined with distance from the moderating effects of the ocean,

leads to seasonal temperature extremes. Mean monthly summer temperatures can readily exceed 86 °F (30 °C) in some places, while mean monthly winter temperatures can fail to reach 32 °F (0 °C). Plants and animals therefore have to display distinct adaptations to survive such extremes.

▲ **Canadian Prairies** *Continentality and a higher latitude bring cold winter conditions to the plains of Saskatchewan.*

North America

Much of the western half of the North American interior is also dry due to distance from the ocean, the greatest distance being over 1,025 miles (1,650 km) near Kyle in South Dakota. The Great Plains grassland prairies of the United States and Canada are effectively drought-prone semiarid regions that also experience seasonal extremes of heat and cold: the northernmost latitude (up to around 53° North) of the Canadian Prairies makes them among the most northerly and coldest drylands on Earth. While the prairies are, in contrast to true deserts, agriculturally productive today, this is generally only achieved by using artificial means of irrigation on soils with poor moisture retention, with much of the region receiving less than 16 inches (400 mm) of mean annual rainfall. Natural grasslands and their extensive fauna have been dramatically altered over the past 200 years by human interventions—including arable cultivation and extensive stock rearing—so are now among the least "natural" drylands on Earth.

A notable feature of some Asian and North American continental deserts and drylands is that the very low temperatures result in snow cover being a major characteristic of long winter months.

Rain shadow deserts

Mountain ranges, especially those parallel to ocean margins, can block the passage of rain-bearing winds and cause rainfall on windward slopes, resulting in drier conditions on their lee (downwind) sides.

Mountain-building, or orogeny, has been particularly important for the development of the deserts and drylands of the western United States and throughout Asia. Mountains also contribute to dryness in parts of the eastern and western Sahara, Australia, and South America.

North and South America

In North America, mountain ranges that stretch from northern Mexico through California to southern Oregon, including the Sierra Madre, Sierra Nevada, and Cascade Range, provide an effective trap for moisture emanating from the eastern Pacific Ocean. This creates the Great Basin and Mojave Deserts in their lee, as well as contributing to the aridity of the subtropical Chihuahuan Desert. Farther east, the extensive Rocky Mountains, extending from Canada to New Mexico, cast a rain shadow on the interior plains and prairies. The geological faulting and rifting that created the region's mountains has formed a series of parallel ridges and troughs with abrupt altitude changes, giving rise to the name Basin and Range Province for the region as a whole.

The uplift of mountain-building has also meant that rivers such as the Colorado have cut deep canyons into the desert landscape. The 5,250 feet (1,600 m) mean elevation Colorado Plateau is also dryland affected by rain shadow factors from the mountains to the west. In South America, the largely semiarid Patagonian and Monte Deserts of Argentina similarly lie in the rain shadow of the Andes Mountains.

Asia

Several desert and dryland areas of Asia result from, or are enhanced by, rain shadow effects. East of the Caspian Sea, for example, the Caucasus Mountains and the Hindu Kush contribute to aridity in the Karakum and Kyzylkum Deserts, while the cold winter semiarid steppe lands of eastern Turkey and Syria are at least in part shadowed by the Taurus and Pontic Mountains. Iran's Lut Desert, which experiences some of the hottest summer temperatures on Earth, is located in an interior mountain-rimmed basin.

Typical landforms

Mountains often have a direct effect on the landforms of their shadow deserts, too. Mountain-sourced rivers, often with a spring peak flow from snow melt, and which may have been more active during past wetter climate conditions, have deposited sediments that form desert salt lakes or provide the material for sand dune formation. Another characteristic landform of many dynamic deserts, notably in North America and Iran, are extensive and distinctive alluvial fans that cover desert-facing mountain slopes.

◣ **Great Sand Dunes**
In Colorado, pockets of dunes have formed where rain shadow conditions and sediments from rivers provide the setting for dunes to develop in the lee of mountains.

▼ **Landlocked desert**
The Hindu Kush mountains provide a significant obstacle for rainfall penetration into the interior drylands of Tajikistan and Afghanistan.

Ocean-margin deserts

Narrow coastal deserts occur on the west coast of several landmasses, due to the impact of cold ocean water on the ability of rain clouds to form. The Namib and Atacama Deserts (see the map opposite) are among the driest places and oldest deserts on Earth.

▼ **Atacama**
Cold fogs called the Camanchaca can bring moisture from the cold ocean to the neighboring hyperarid desert landscape.

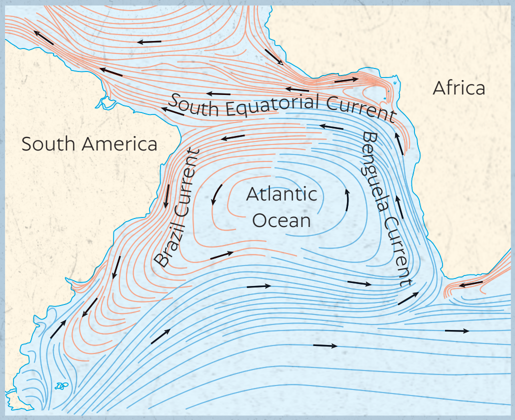
Where cold Southern (Antarctic) Ocean water currents upwell and reach the ocean surface in the subtropics in latitudes 15–34° South, they have the effect of cooling the lower atmosphere, enhancing the aridifying effects of descending stable subtropical air. The cold water both limits the ability of rain clouds to form over the ocean through convection, and creates fog through condensation as cold air has a lower capacity than warm air to store water vapor. These conditions then affect neighboring coastal areas, creating narrow deserts up to 1,200 miles (2,000 km) long and extending inland for up to 100 miles (160 km). The rotation of the Earth means that currents tend to flow along the west coast of landmasses.

While the Namib (and its northern extensions) and Atacama Deserts are the most distinctive manifestation of the aridifying effects of cold southern-hemisphere ocean currents, the same processes occur to a lesser degree on the west coast of Australia. In the northern hemisphere, cold currents originating in the Arctic Ocean have a similar effect on the coast of the United States and Baja California in Mexico, enhancing dryness in the Sonoran Desert, as well as in the Canary Islands off the west coast of Africa's Sahara Desert.

In the most coastal parts of these deserts, fog can be the dominant source of moisture, amounting to only a few millimeters of precipitation each year. The Namib and Atacama are renowned for the specialist animal and plant adaptations to this unusual dominant moisture source. While some parts of these deserts are represented by rocky landscapes, the coastal locations can result in wave action bringing significant quantities of sediment to the dry coastline. Strong onshore winds transport this material inland, building in the Namib a distinctive "sand sea" that possesses some of the biggest dunes on Earth, up to 1,000 feet (300 m) high.

GLOBAL MAP OF COLD CURRENTS AND ASSOCIATED DESERTS

Cold-water currents contribute to aridity in west-coast deserts—notably the Namib, Atacama, and Sonoran Deserts, but also in western Australia and the Canary Islands off the Saharan coast. The inset shows how the Benguela Current, which cools the southern African west coast, forms part of a more extensive ocean-water circulation system called the South Atlantic Gyre. Warm surface water is shown in orange; cold surface water is blue.



Is Antarctica a desert?

As well as being extremely cold and windy, Antarctica receives the least precipitation of all the Earth's continents—conditions that together favor aridity. Extremely cold air simply cannot transfer sufficient water from surrounding oceans to generate much precipitation: what small amounts occur are almost exclusively in the form of snow. Technically, precipitation levels are well within the values that are usually considered to designate desert conditions. But is Antarctica really a desert?

McMurdo Station, a research facility on the coastal tip of Antarctica's Ross Island, receives on average 7.9 inches (200 mm) of precipitation a year. Another, the Amundsen-Scott South Pole Station—more than 740 miles (1,200 km) from the landmass margin—has recorded on average 2 inches (50 mm) of precipitation per year. At Vostok Station, which is located at the southern geomagnetic pole, less than 0.2 inches (5 mm) of annual precipitation is recorded, making it one of the very driest (and, with a mean temperature of -67 °F [-55 °C], coldest!) places on Earth.

Antarctica can also be very windy, and wind provides an important mechanism for the movement of sediment and loose material in dry environments that lack protective vegetation. The British Antarctic Survey runs six research stations on the continent. They report generally moderate wind-speed conditions year-round, with a mean speed of 6 meters (19.7 ft) per second (m/s), which is around the threshold speed at which loose particles start to be blown around. Also notable is that over 40 days a year are reported to experience gales, when wind speeds exceed 30 m/s (98 ft/s), and even hurricane-force gusts (over 55 m/s [180 ft/s]). One factor that makes Antarctica generally windy is its high plateau nature. Cold air flows off this surface toward lower coastal areas, in what are called katabatic winds, which can make the margins of the continent particularly windy places.

On precipitation criteria alone, Antarctica could therefore be regarded as a desert, while its windiness also favors some of the common attributes of desert environments. Why is it not therefore formally recognized as a desert by organizations such as the United Nations Environment Programme?

To understand why, it is necessary to appreciate the scientific evolution of desert research during the twentieth century.

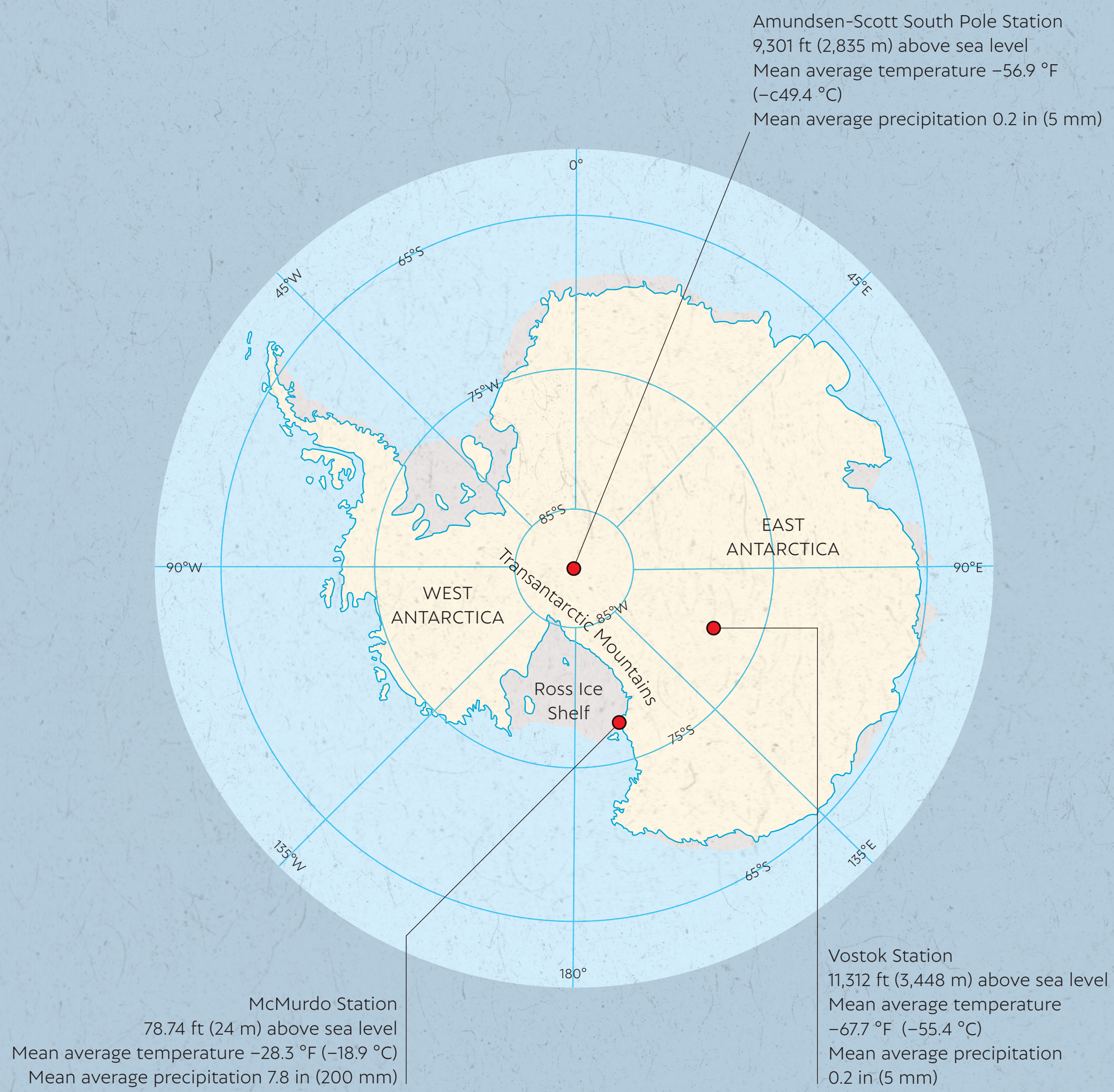
Land classifications

Following World War II, global concern rose regarding support for human populations living in drought-prone and dryland conditions. As a result, the United Nations Educational, Scientific and Cultural Organization (UNESCO) commenced a program concerning global food production, out of which grew analyses of aridity and the classification of land areas. The early work of the American geographer Peveril Meigs was especially influential in this regard, and remains so today. In 1953 his aridity scheme, produced for UNESCO, classified deserts and drylands based not only on their effective precipitation amounts, but on temperatures being *sufficient for crop growth*. Thus Antarctica was, and continues to be, excluded from UN designations of desert areas.

That most of Antarctica is ice-covered—only 0.4 percent is not—also favors its exclusion from areas regarded as deserts, as most of its land surface is not exposed to the elements and therefore does not experience the direct impacts of atmospheric conditions and associated environmental processes. Contrastingly, seasonally very cold, and winter-snow covered, continental dry regions, such as the Gobi of Mongolia, are recognized as deserts because summer months are snow-free and warm enough for crop growth.

POLAR DESERT?

Data from the few weather stations in Antarctica show that this continent is, in fact, the Earth's driest.



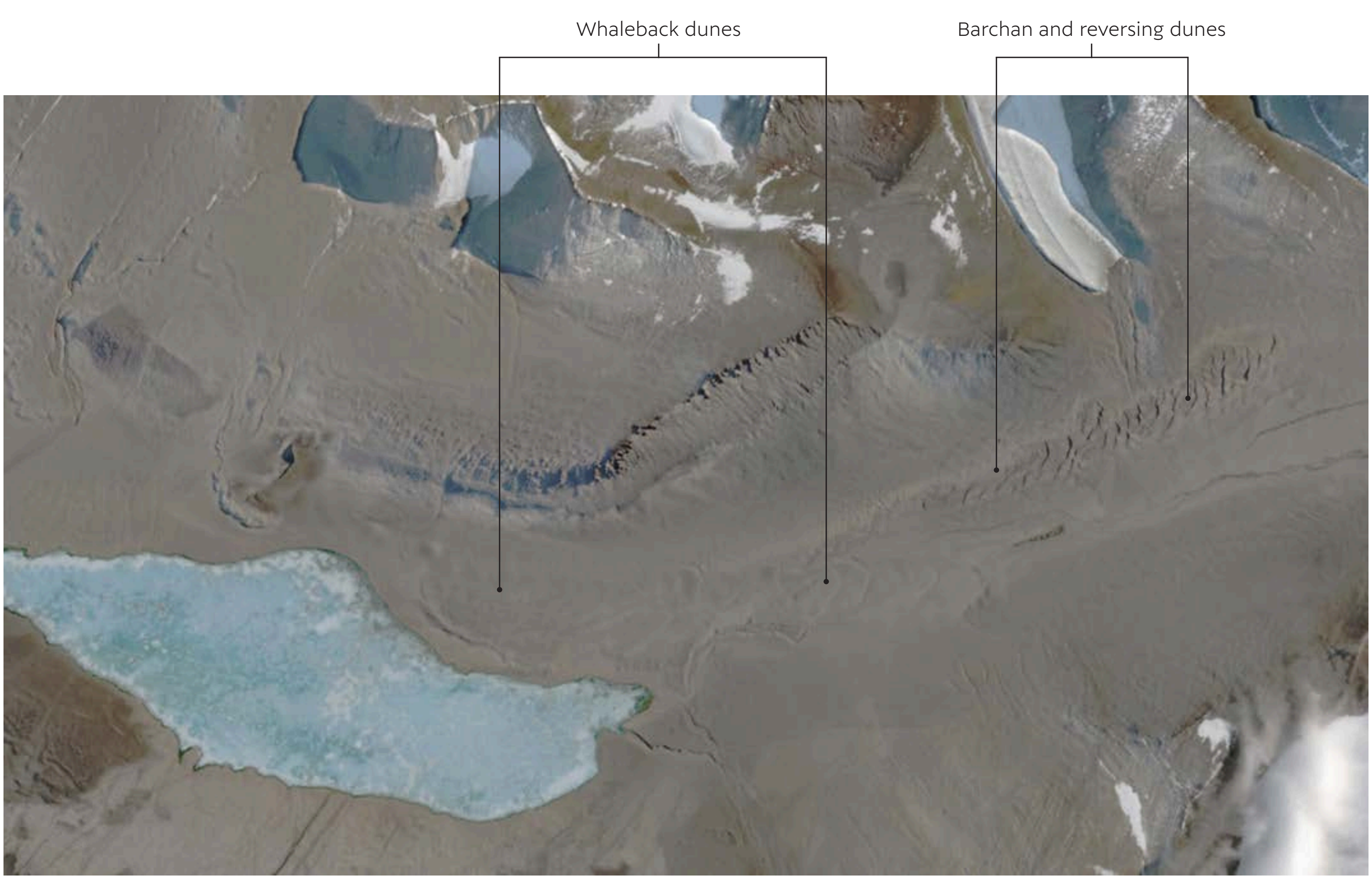
Dry valley dunes
Dry valley dunes provide an unusual landscape feature in a unique ice-free part of Antarctica.

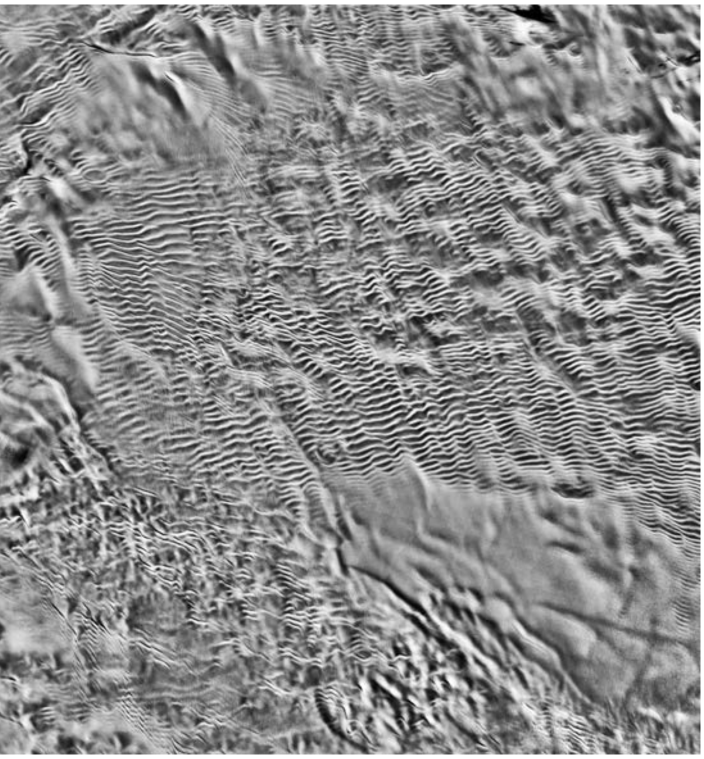
The dunes of Antarctica

Antarctica is not a place where you would generally expect to find sand dunes, but there are circumstances on the continent where environmental conditions align to make their formation possible. As conditions of very low temperatures, aridity, and windiness are common on other planetary bodies, where unmanned exploration has led to the identification of extensive dune fields, the Antarctic dunes may be important analogs for their interpretation.

The Victoria Valley of Ross Island is one of a series of "dry valleys" near the Antarctic coast that are glacier-free in their lower reaches. Fine sand-sized sediment on the valley floor has accumulated in a glacial-outwash sand sheet, from material eroded by the Victoria Glacier and sourced from frost-weathered rocks exposed in the steep valley sides. The valley's aridity and its windiness, assisted by the funnelling effect of the valley itself, provide unique local conditions that have allowed aeolian sand dunes to form in this ice-free part of the continent. Initially scientifically investigated in the 1960s, the first data on these dunes appeared in the 1970s, including a detailed field analysis in 1974, as interest grew in their potential as analogs for Martian dunes. Subsequent research has applied advanced methods such as ground penetrating radar (GPR), to understand the dunes' internal structures and luminescence dating, which measures when sand grains became buried and therefore when they were deposited or ceased to be moved by the wind, allowing their age and rate of movement to be established.

The main dune field occurs in a belt that is just 2.2 miles (3.5 km) long and 0.6 miles (1 km) wide. Dunes are formed of sand blown westward in "summer" months from the sand sheet, and are mostly barchan dune forms, mobile features with distinct slip faces on their downwind edges. Northwesterly katabatic winds, however, cause





some seasonal reversal in movement direction so that some of the features may be what are known as reversing dunes. Individual dunes are up to around 1,950 feet (600 m) from tip to tip and can be over 30 feet (10 m) high. Close to the sand sheet, another dune patch comprises features that are formed of coarser sand and have no slip faces and a generally rounded profile. These so-called “whaleback dunes” also have an active surface layer including a capping of gritty sediments, while their interiors are reported to be largely frozen.

GPR surveys of the barchan and reversing dunes have also revealed dune interiors that include distinct frozen snow layers within the stratified sand. Samples collected for luminescence dating show that the oldest dune sediments were deposited around 1,300 years ago. The dunes remained stable until around 300 years ago, when circulation strengthened; movement today, at a rate of around 5 feet (1.5 m) per year, may now be heightened in association with temperature rises due to anthropogenic global warming.

Satellite imagery has also revealed extensive dunelike patterns over large swathes of Antarctica’s interior plateau. These are snow forms upon the ice sheet surface, up to 26 feet (8 m) high, with wavelengths that can be as long as 3.7 miles (6 km). Relative to sand dunes, these generate low, undulating surfaces, but they undoubtedly owe their existence to the transportation of dry snow and ice particles by strong katabatic winds.

Whether these features and the mobile dunes of the dry valleys are sufficient evidence to warrant Antarctica being regarded as a true desert landscape is not clear; however, it is certainly one of the largest dry regions on Earth, and it possesses marked evidence of the wind being an important environmental agency in shaping the surface of its landscape.

◤ **Snow dunes**
High on Antarctica’s bleak interior, satellite images have revealed fields of dunelike features formed from snow.

▲ **Polar sand dunes**
The dry valley dunes in Antarctica are formed of more usual material: sands washed out from under the ice sheet.

3

Mapping deserts

Early maps

Mapping of deserts has occurred since prehistoric times, witnessed in rock art from the Sahara and Arabia. In this section we explore the history of desert mapping, from prehistory to the latest technological developments. The following pages draw extensively, but not exclusively, on the Sahara Desert and surrounding regions, where many mapping developments have played out and can be well illustrated.

The world's earliest maplike drawings come in fact from drylands. In the deserts of Saudi Arabia and Jordan there are remarkable 9,000-year-old plan-view rock etchings of gigantic stone structures known as kites, used to aid hunting of wild animals. Amazingly, the remains of these structures still exist today (see pages 188–189). Their makers had the uncanny ability to depict them accurately in their stone-engraved plans, despite not being able to see the kites from above. There is then little evidence of further developments in mapping from anywhere until about

Early surveyors
A painting showing Egyptian surveyors using a knotted rope to measure property dimensions.

2,600 years ago, with conception of the first map of the world, the Imago Mundi. This is a clay tablet centered on ancient Babylon and surrounding desert regions in present-day Iraq, but it also depicts the rest of the known world of its maker, albeit in a stylized and schematic manner.

Early Egyptian art exhibits many aspects of mapping, at a similar time to the Imago Mundi. For example, the lid of a 2,400-year-old stone sarcophagus (coffin) bears a circular depiction of Egypt and the surrounding regions. An inner circle shows numerous standards associated with the ancient territorial divisions of Egypt, and an outer ring depicts its neighboring peoples. The goddesses of east and west are shown on the left and right of the outer ring respectively, thus allowing orientation of the inscription. By 1,150 years ago, Egyptian cartography had developed considerably, as evidenced by the Turin Papyrus, a map showing the location of a quarry deep in the desert that was to be reopened in order to acquire stone to build statues for the pharaoh Ramesses IV. This map is particularly important as it contains the earliest surviving depiction of topography.

Though the Turin Papyrus has no scale, it is clear that the Egyptians could measure distance accurately, as evidenced by archaeological finds of a surveying instrument known as a merchet, as well as sticks and ropes. The Egyptians also used a unit of measurement known as a cubit, derived from the distance from the elbow to the tip of the middle finger. Because a few plans of buildings have survived, we know that the cubit, and the instruments developed to measure it, were used to survey and map urban areas. Pictures of surveyors measuring fields have also been discovered, indicating that they were used to make larger-scale maps showing land ownership too. Maps were also perhaps used to show trade routes across the Sahara. We know that the latter existed in Egyptian times and their users would have benefited considerably from the knowledge used to prepare them. For example, there is a line

of archaeological sites known as the Abu Ballas Trail that stretches some 250 miles (400 km) from Dakhla Oasis to the Gilf Kebir in the central Sahara. The site of Abu Ballas itself, which means "Father of Jars," is a large pottery depot—one of many used to store water for the people and donkeys that used the trail. The first map to include geographical details of the Sahara was made by the Egyptian Claudius Ptolemy. Born around 100 CE, Ptolemy lived on the coast at Alexandria, where he had access to what was at the time the world's greatest library. He was an expert in mathematics, astronomy, astrology, geography, and music, and wrote numerous books on these subjects, including what is known as the *Geographia*. The *Geographia* explained how to draw maps using geographical coordinates based on a map projection. It then described how to use astronomical data to establish accurate locations, but also how to use less-precise travelers' reports when these were not available. Ptolemy collated vast amounts of geographical information using these methods and employed it to construct a ground-breaking map of the known world at the time. Though the map did not have the specific aim of mapping deserts, it did so where they were known. However, even though Ptolemy lived on the edge of the Sahara, the map shows less detail here than it does elsewhere, suggesting a paucity of travelers' reports from such a harsh environment.

Furthermore, we now know that Ptolemy's world map contained many errors for the Sahara region, which, despite its proximity to Egypt, is not even portrayed as a desert. Instead, it incorrectly shows the north-central Sahara as being drained from east to west by a large river system feeding numerous lakes along the way and eventually debouching into the Atlantic Ocean. In contrast, the mapping of the River Nile has stood the test of time, being relatively accurate—presumably because it had been an important trade route for thousands of years. The lesson to be learned from this map is that relying solely on a small number of travelers' reports, as Ptolemy appears to have done for the Sahara, can lead to erroneous results.

◀ **Ptolemy world map**
Produced in the Greco-Roman era, this map was later reproduced in an embellished form by Lord Nicolas the German in 1482. It shows a largely empty Sahara in its lower left-hand quadrant.

Mapping from exploration

The mapping techniques laid down by Ptolemy appear to have been lost during the Dark Ages that followed the collapse of the Roman Empire, but a renaissance in desert mapping seems to have begun in the twelfth century CE.

No maps of the Sahara that we have evidence of today appear to have been produced for around a thousand years after Ptolemy's time. A renaissance in Saharan mapping started with Muhammad al-Idrisi (1100–65), who spent his early life travelling in North Africa, then moved to Europe, where he continued his travels while also embarking on a career in geography and cartography. He is best known for the Tabula Rogeriana, a map of the known world that included a remarkable amount of detail on the location of settlements, mountain ranges, and rivers. For the Sahara, the map was a significant development. It contains much more detail than Ptolemy's map, showing numerous previously unrecorded settlements. However, there is one obvious similarity—it indicates the erroneous east-west river crossing the Sahara that Ptolemy's map introduced.

(continued...)

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