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Case report

Birth of the Taklamakan Desert: When and How?

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Abstract: The Taklimakan Desert is one of the largest deserts and sand seas in the world and plays a critical role in the global aerosol (eolian dust) system, impacting both climate and ecosystems on continents and over oceans. Geological evidence suggests that much of the western part of the Tarim Basin, which is now covered by the vast sandy desert, was once the eastern fringe of the Paratethys Sea. After the retreat of the sea, the area transformed into a fluvial system before becoming an mountain front alluvial fan system due to the uplift of the northern Tibetan Plateau. Deserts developed during this period, as sand dunes and eolian loess deposits were formed and buried to become part of the sedimentary sequence. Dating of these sequences suggests that the Taklimakan Desert, in a similar form to what we observe today, came into existence no later than 25 million years ago. Taklimakan Desert was formed as a response to a combination of widespread regional aridification due to the rain shadow effect and increased erosion in the surrounding mountain fronts, both of which are closely linked to the tectonic uplift of the Tibetan-Pamir Plateau and Tian Shan, which had reached a climatically sensitive threshold at this time.

Keywords: Cenozoic Era, desertification, Taklimakan Desert, Trim Basin, uplift of Tibetan Plateau

1. Introduction

Deserts are regions that receive very little rainfall, typically less than 250 millimeters of precipitation per year. They are often characterized by extreme temperatures, with hot days and cold nights. The world's deserts are located across various continents, including Africa, Asia, North America, South America, and Australia, occupying about one-third of the surface of the Earth (Figure. 1). The largest hot desert in the world is the Sahara Desert in Africa, which covers over 3.6 million square miles. Deserts are generally located in the tropics or subtropics, which are latitudinal zones that lie between about 23.5 ° north and south of the equator. However, there are also some deserts located in higher latitudes, particularly in the cold deserts found in the Arctic and Antarctic regions.

Deserts play an important role in the Earth's ecosystem. Understanding their unique characteristics and the adaptations of the plants and animals that inhabit them can help us better appreciate their ecological significance and the challenges they face. Deserts are home to a variety of unique plants and animals that have evolved to survive in the harsh conditions. These adaptations not only allow them to thrive in the desert environment but also have broader ecological significance. For instance, the deep root systems and water storage mechanisms of desert plants can help prevent erosion and improve soil quality, while the heat-dissipating adaptations of desert animals can inform the development of thermal management technologies for human use.

Moreover, deserts are also a crucial source of eolian dust, which plays a significant role in the Earth's climate system and ocean ecosystem (Figure 1). Eolian dust, also known as aerosol, is a type of airborne particulate matter that originates from arid and semi-arid regions of the Earth's surface. These regions include deserts, steppes, and drylands, where there is limited vegetation and high wind speeds, causing the fine-grained particles to become easily lifted and carried by the wind [1,2].

One of the primary effects of eolian dust on climate is its ability to reflect sunlight. The high reflectivity, or albedo, of eolian dust particles means that they can reflect a significant amount of sunlight back into space. This reflection can lead to a cooling effect on the Earth's surface, which can offset some of the warming caused by greenhouse gas emissions. Eolian dust can also influence the Earth's climate system through its effects on cloud formation. When eolian dust particles are deposited on the ocean surface, they can act as cloud condensation nuclei, providing a surface for water vapor to condense and form clouds. This process can affect the reflectivity of the Earth's surface, or albedo, which in turn can influence the amount of solar radiation that is absorbed or reflected by the planet. Changes in the amount of eolian dust that is deposited on the ocean surface can therefore have significant implications for the Earth's climate.

One of the most important roles that eolian dust plays in the ocean ecosystem is as a source of nutrients. Eolian dust contains a range of minerals and nutrients, including iron, phosphorus, and silica, which are essential for the growth of marine phytoplankton. Phytoplankton are microscopic photosynthetic organisms that form the base of the marine food web, and they are responsible for a significant amount of the world's oxygen production. By providing a source of nutrients, eolian dust can stimulate the growth of phytoplankton, which can in turn support higher trophic levels in the food web.

In addition to its role in nutrient cycling, eolian dust can also influence the productivity of the ocean ecosystem through its effects on ocean fertilization. When eolian dust reaches the ocean, it can provide a source of iron that can stimulate the growth of phytoplankton. This process is known as ocean fertilization, and it can increase the amount of carbon dioxide that is absorbed from the atmosphere and stored in the ocean. This has important implications for the global carbon cycle, as the oceans are one of the largest sinks for atmospheric carbon dioxide.

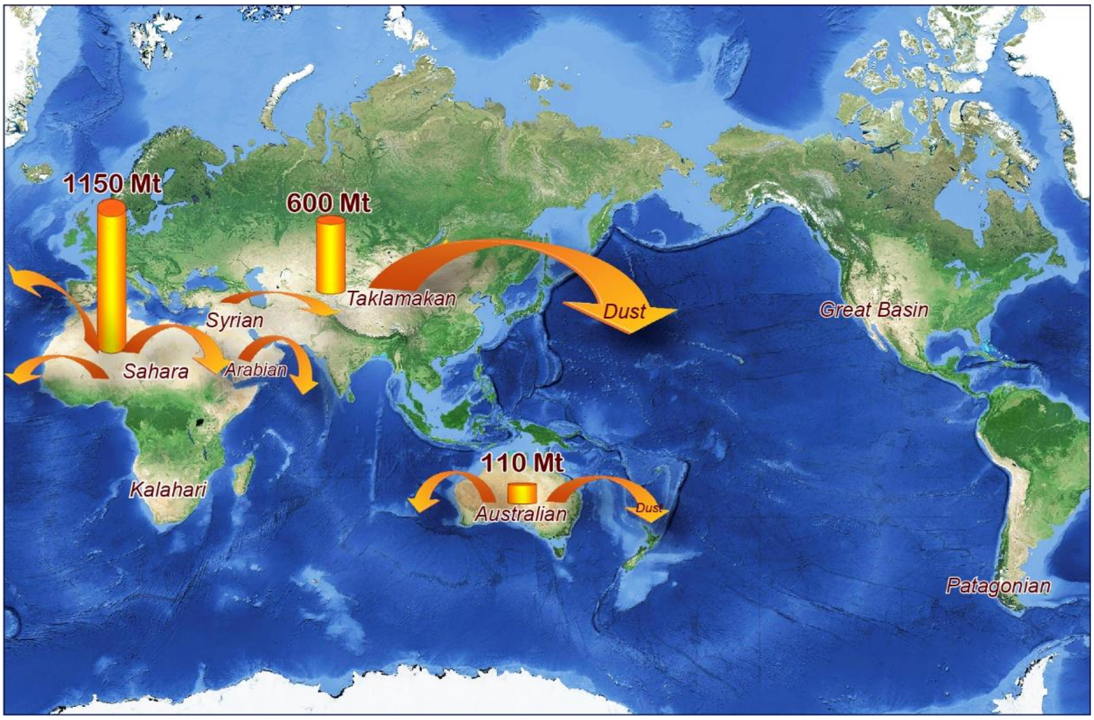

Figure 1. Map showing the distribution of deserts in the world. Major deserts are marked by names. Cylinders indicate dust emission (given in Mt/yr) from major source areas. Taklamakan Desert is marked to represent the arid region of Asian interior. Arrows indicate paths of dust transport. Modified after [1,2].

2. Taklamakan Desert: More than just sand dunes

The Taklamakan Desert is located in the Xinjiang Uyghur Autonomous Region of China, in the northwest of the country. It covers an area of approximately 337,000 square kilometers, making it the second-largest shifting-sand desert in the world after the Sahara (Figure 1). The desert is bordered by the Kunlun Mountains to the south and the Tien Shan Mountains to the north (Figure 2A). The desert's name is derived from the Uyghur language and means "the place of no return", or "sea of death", highlighting the harsh and inhospitable nature of the desert.

One of the defining features of the Taklamakan Desert is its vast sand dunes. The sand dunes in the Taklamakan Desert can reach heights of up to 200 meters, and they constantly shift and move due to the high winds in the region. The dunes are formed by the accumulation of sand grains that are transported by the wind, a process known as eolian transport. The shape and size of the dunes depend on the direction and strength of the wind, and they can be classified into different types, including longitudinal dunes, barchan dunes, and star dunes (Figure 2 B & C).

In addition to sand dunes, the Taklamakan Desert is also known for its significant eolian dust production. Provenance studies suggest that mineral dust from the Taklimakan Desert contributes substantially to the global aerosol system, allowing it to play a significant role in modulating global climate on various time scales [3]. The formation of the Taklimakan Desert therefore marked a major environmental event in central Asia during the Cenozoic Era (the latest 65 million years of the

Earth's history), with far-reaching impacts. Furthermore, determining when and how the desert formed holds the key to better understanding the nature of tectonic-climatic linkage in this critical region. However, the time at which the Taklimakan Desert came into existence has been strongly debated over decades, with estimates ranging from only a few hundreds of thousands to a few million years ago [4]. Much recent study by us suggested that Taklamakan Desert was born no later than 25 million years ago [5].

Figure 2. Photos showing Taklamakan Desert and surrounding mountains. A, Location map; B and C, Sand dunes in Taklamakan Desert; D, Pamir Mountains; E, West Kunlun Mountains; F, Alluvial fan system in front of West Kunlun, showing desert and loess deposits of recent age.

3. Tarim Basin: Once a shallow sea

The Taklamakan Desert currently covers a vast area known as the Tarim Basin in geological term. The basin is bordered by the Tien Shan Mountains to the north, and the Pamir and West Kunlun Mountains to the south and southwest (Figure 2). Over millions of years, the Tarim Basin has undergone a complex history of evolution, with the latest episode being particularly relevant to the scope of this study.

During the Cretaceous and Paleogene (arbitrarily about 100 to 50 million years ago), a shallow epicontinental sea extended across Eurasia from the Mediterranean Tethys to the Tarim Basin (Figure 3), which is known as the Paratethys Sea. It was a large, shallow sea covering a vast area that included parts of Europe, Asia, and Africa.

The geological and environmental history of the Paratethys Sea has been studied extensively by scientists, and it has been found to have played a significant role in the development of the landscape and climate of the regions that surrounded it. The Paratethys Sea eventually began to shrink due to the collision of the Eurasian and African tectonic plates, which caused the sea floor to rise and the sea level to fall. Today, much of the area that was once covered by the Paratethys Sea is now land, including parts of the Mediterranean Basin and Central Asia.

From latest Cretaceous to early Paleogene, much of the western Tarim Basin was influenced episodically by the Paratethys Sea. Shallow marine strata of this age are observed extensively along the western and southwestern margins of the Tarim Basin, extending to Hotan to the east and Ulugqat to the north (Figure 3). Five marine incursions have been recognized in the broad region, with the fourth being the final one at Aertashi where it is represented by the Wulagen Formation (Stage I in Figure 4). Recent biostratigraphic work at Aertashi has suggested that the Paratethys Sea finally retreated from this locality at ~41 Ma [6], a process that has been attributed to global eustasy coupled with tectonism associated with the Indo-Asia tectonic plate collision and subsequent uplift of Tibetan Plateau. Together these have amplified the aridification of the Asian interior [7].

Figure 3. Schematic map showing the Paratethys Sea and Tarim Basin during Paleocene and Eocene (about 65-41 million year ago). Modified after [6].

4. From lacustrine/fluvial plain to mountain front alluvial fan

The sedimentary sequences within and along the southwestern margin of Tarim Basin preserve the evolutionary history of regional tectonism, paleo-geography and paleoenvironment [8–11]. Along the profile near the village of Aertashi, the sequence begins with the limestone unit contain abundant giant bivalve fossils, indicating shallow sea deposition (Stage I in Figure 4). The Paratethys Sea eventually retreated completely from this region due to the uplift of the northern Tibetan Plateau. Syntectonic foreland basin (basin developed in the front of a mountain simultaneously with the uplift of the mountain) the deposition followed immediately after the marine regression and lead to accumulation of thick continental red beds (reddish sandstone and siltstone formed in relatively arid climate), known as the Bushiblake Formation (Stage II in Figure 4). It is characterized by red, fine-gained mudstone and fine sandstone, with common evaporative gypsum, typical of low-energy, meandering river, lacustrine and playa deposits. The overlying Wuqia Group consists of thickly bedded sandstones with minor mudstone. The overall content of sand increases upward, as does the grain size (Figure 5).

Lithofacies (a term used to describe the combination of lithology and interpreted sedimentary environments) change to distal alluvial fan deposits, consisting of conglomerate, sandstone and siltstone crossing the boundary from the Wuqia Group to the Artux Formation (Stage III in Figure 4). The conglomerate layers in the Artux Formation are thin-bedded debris flow deposits, containing medium-sized, angular to sub-rounded pebbles, of which more than half are sedimentary rocks. The overlying Xiyu Formation is up to 3 km thick and consists of massive boulder to cobble-grade conglomerate with increasing volumes of igneous and high-grade metamorphic clasts. The Xiyu Formation is typical of proximal diluvial fan deposits derived from unroofed mountain belts. Red beds passing upward into upward-coarsening conglomerate and debris-flow deposits recorded the change in paleoslope and sediment supply related to uplift of the northern margin of the Tibetan Plateau and Pamir (Figure 5).

It is a common practice for geologists to synthesize the rocks observed in the field and combine the interpreted sedimentary environments into a column, as shown in Figure 5. This helps to reconstruct and illustrate the evolutionary history of the Tarim Basin, which is termed basin analysis. The stratigraphy and lithology column depicts the rock types in the sequence and the sedimentary environments in which they were formed. Analysis of the rocks and sedimentary structures also allows scientists to investigate the tectonic activities of the mountains. In this case, a coupling mountain-basin system is put together so that scientists are able to comprehend a full picture of what has happened in the system. In the next section, we will discuss how information about the eolian activity in the region, which is crucial to understanding the birth of the Taklamakan Desert, is extracted from the geological evidence.

Figure 4. Sedimentary sequences along the southwestern margin of Tarim Basin, which preserve the evolutionary history of regional tectonism, geomorphology and paleoenvironments. The thick blue line indicates a visualized geological time axis, representing the ages of sediments upward (not to scale). Interpreted environments were obtained through the analysis of the sedimentary sequences and presented as visualized scenes. Synthesized evolutionary history of Tarim Basin is given in Figure 5.

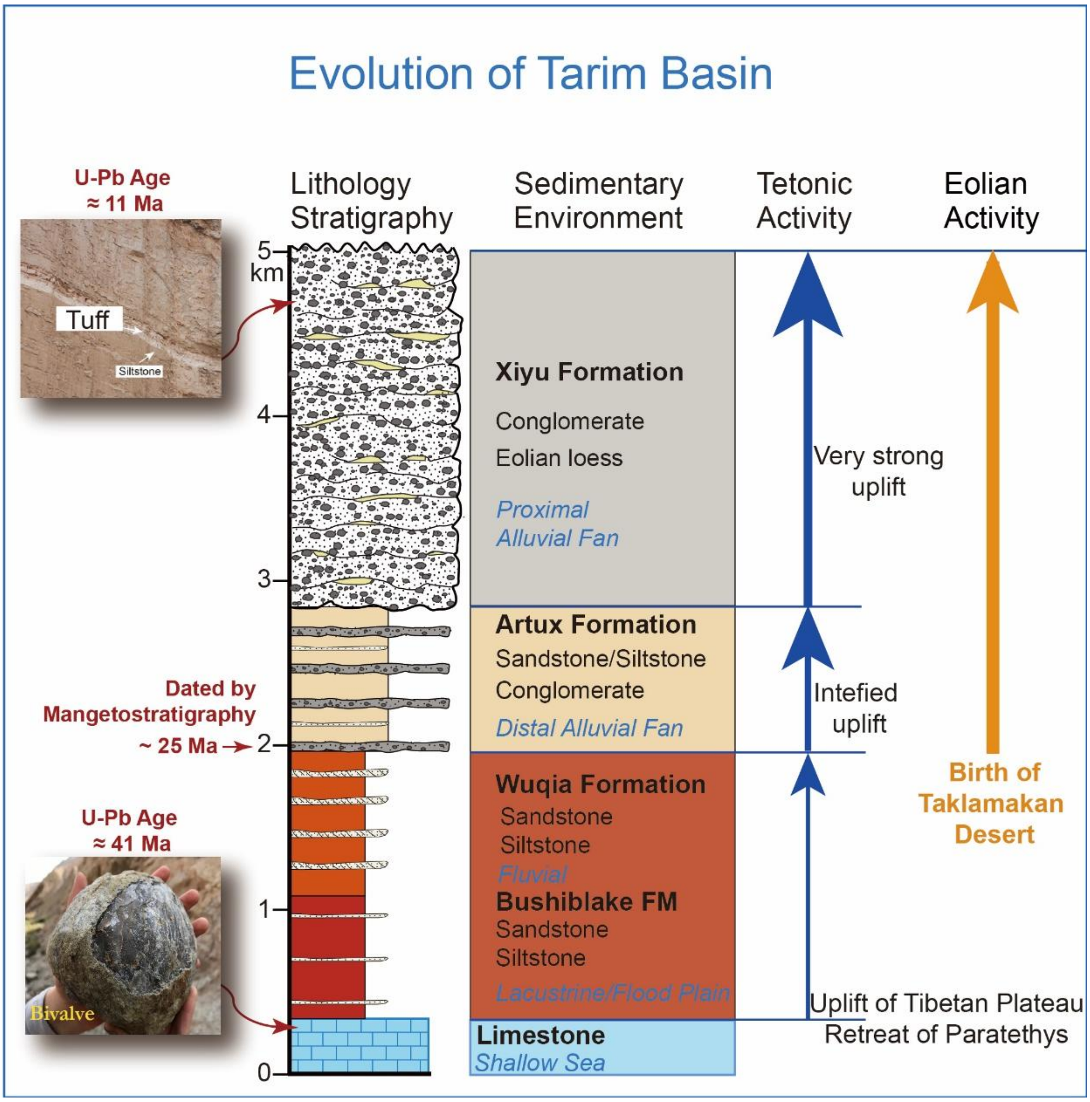

Figure 5. Schematic diagram showing the lithology, stratigraphy and interpreted environments of the sedimentary sequences along the southwestern margin of Tarim Basin. The evolutionary history of Tarim Basin is also reconstructed. Modified after [10].

5. Birth of the Taklamakan Desert: Geological evidence and dating

In a mobile sand sea such as the Taklamakan Desert, sand dunes keep migrating and being reworked constantly, so that the evidence of the existence of an 'old desert' would have usually been destroyed. In this case, finding the geological evidence of the 'old desert' is an essential issue of the study. Fortunately, some evidence has been preserved, mostly taking the form of either 'buried dune sand' or 'eolian loess deposit' in the strata, which bears great potential for determining the evolutionary history of the Taklamakan Desert [5].

Direct evidence of desert deposit is found in the exposed sedimentary sequence at the Mazatagh Range, in the central Taklimakan Desert (Figure 1A & Figure 6A). The lithostratigraphy at this location has well been established and can be generally correlated to the basin margin sequences (Figure 5), except that the lithologies are generally finer and sedimentation rates are lower because of its more distal location. Red cross-bedded eolian sandstone (Figure 6) is present in the red bed unit as isolated sandstone lenses, likely indicating an initial stage of a desertified environment which was composed of low energy fluvial, playa lakes and associated lunette dunes. The most prominent sedimentary unit in the Mazatagh sequence is the well-developed, cross-bedded, yellowish sandstone (Figure 6). It is about 200 m thick, stratigraphically continuous and is interpreted as typical desert sand dune deposits.

Figure 6. Photos of sedimentary sequences of Mazatagh Range in central Tarim Basin (Taklamakan Desert), showing buried eolian sand dune deposits, indicating the existence of the 'old' Taklamakan Desert.

As discussed above, Artux and Xiyu Formations, which make the upmost part of the sedimentary sequence, are of alluvial fan deposits, consisting of poorly sorted, boulder-sized, angular gravels (conglomerate) and coarse sandstone. However, the massive siltstone lenses intercalated in the Artux and Xiyu Formations at Kekeya and many other localities are particularly noteworthy (Figure 7). Previous sedimentological studies, including facies investigations, grain size and geochemical analyses suggest that these siltstone lenses are eolian loess, having been sourced from the desert, deposited and preserved on an intermittent alluvial and diluvial fan system [9], an Earth surface process resembling to the Taklimakan Desert today.

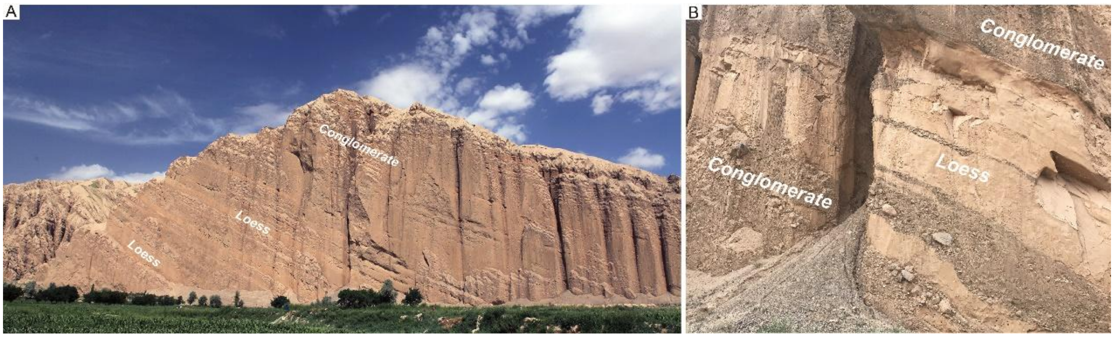

Figure 7. Photos of Xiyu Formation from Yecheng Section, showing siltstone interbedded with conglomerate. The siltstone is of eolian loess deposit, originated from alluvial fans and the desert, thus indicating the existence of 'old' desert in the Tarim Basin.

Loess is a type of sedimentary deposit primarily made up of silt-sized particles that have been carried by the wind and deposited in layers over time. These deposits are typically found in regions that have experienced arid or semi-arid climates and have been subject to intense wind erosion. One of the most famous and extensive loess deposits in the world is found in China, covering an area of over 600,000 km^2 known as the Chinese Loess Plateau.

Loess and desert deposits are genetically linked, at least in the case of the Taklamakan Desert. Sediments in the broad Tarim Basin are generally classified into three types: desert sand, gobi gravel, and loess, distributed in a circular pattern. The central area contains vast shifting sand dunes known as the typical desert, surrounded by a zone of gravels called the Gobi belt (refer to Figure 8).

The Gobi belt makes up the surface of the giant modern alluvial fan systems that connect the desert with the mountain front. Both fluvial and eolian processes operate on the gobi belt, sorting the sediments into different size fractions. The sand-sized fraction is transported to the basin to become the desert, and the finer fraction (silt-sized fraction) is deflated, transported, and deposited in front of the mountain to form loess (Figure 8).

Loess deposits are generally distributed as the outer ring of the Tarim Basin. Although loess is easily eroded, it can be preserved when it is deposited on the surface of the alluvial fans and buried by younger sediments. This is exactly what happened to the loess in the Xiyu Formation, which was buried by conglomerate and preserved.

In summary, deposition of both eolian sand dunes in the basin center, and the genetically equivalent eolian loess along the basin margins provides two lines of evidence to suggest that the Taklimakan Desert come into existence when these deposits were formed.

The next critical issue is to date the sedimentary sequences. The last few decades have witnessed great advances in dating technology, particularly in radiometric dating techniques. The bivalve fossil (carbonate) from the Paratethys Sea unit has been dated by U-Pb laser-abrasion ICP-MS to be about 41 Ma (million years). The volcanic ash from the conglomerate from Yecheng section has been dated by U-Pb laser abrasion ICP-MS to be about 11 Ma. The sediments in between have been dated by paleomagnetism (magnetostratigraphy). The onset of Taklimakan Desert has been dated to be about 25 Ma (Figure 5).

6. Uplift of Tibetan Plateau: The formation of rain shadow and dust factory

The formation of a desert over geological time scales relies on two integral prerequisite conditions: an arid climate and a substantial supply of sand [2].

Firstly, an arid climate. During much of the Cretaceous and Paleocene (arbitrarily from about 100 to 50 million years ago), Tarim Basin joined the reset of east China to form a roughly zonal region between 30–50 ℃N, which was under the influence of the northern westerlies with a relatively arid climate [12]. Retreat of Paratethys Sea decreased significantly the moister brought by the westerlies thus causing further aridity to Tarim Basin. However, it was not until the time when Tibetan–Pamir Plateau and Tien Shan uplifted to a critical elevation to create a rain shadow that the area evolved into full aridity.

A rain shadow is an area of significantly reduced rainfall located behind a mountainous region on the side facing away from prevailing winds, known as the leeward side. Moisture from water bodies, such as oceans and large lakes, evaporates and is carried by onshore breezes towards drier and hotter inland areas. However, when the moist air encounters elevated landforms, it is driven upslope towards the peak. As the air rises, it expands, cools, and its moisture condenses and precipitates, causing most of the humidity to be lost on the windward side (also known as the rainward side) before reaching the top. As the air descends the leeward side of the landforms, it is compressed and heated, producing foehn winds that absorb moisture downslope and create a dry climate region behind the mountain crests. This climate typically takes the form of shrub-steppe or even deserts.

Secondly, a substantial supply of sand. The formation of the desert also requires abundant material supplies. The tectonic uplift of the Tien Shan Mountains, Pamirs and West Kunlun Mountains resulted in a large amount of rock being weathered and eroded. The weathering products were transported to the basin through alluvial processes, producing desert and dust through sorting. The dust not only settled in front of nearby mountains to form loess, but also transported to eastern Asia (such as the Loess Plateau region), the Pacific region, and even the Arctic region through the westerlies, becoming an important component of the global dust system.

The concept of a **dust factory** is used here to decipher the tectonic, sedimentological, and eolian processes responsible for producing eolian dust [2] (Figure 7). The uplift-induced erosion and weathering of bedrock produce abundant ground material, usually called sediments. These sediments then travel down the slopes to form alluvial and diluvial fans in front of the mountains. As they travel down to the basin, they undergo a series of fluvial and eolian processes that sort them into different size fractions, such as sand and silt, with the former becoming the constituents of a desert, and the latter being deflated and transported further as eolian dust. Eolian dust, which is deposited in a proximal destiny, is called loess. The dust which is transported over long distances is conventionally called aerosol. Therefore, a dust factory consists of a dynamic chain involving the tectonic uplift of a mountain, erosion of bedrocks into sediments, transportation, sorting, and deposition of sediments, formation of deserts, loess, and eolian dust. In the case of the Taklamakan Desert, such a dust factory has been in operation since at least the late Oligocene as a direct response to a combination of widespread regional aridification due to the rain shadow effect and increased supply of sediments resulting from unroofing and erosion in the surrounding mountains.

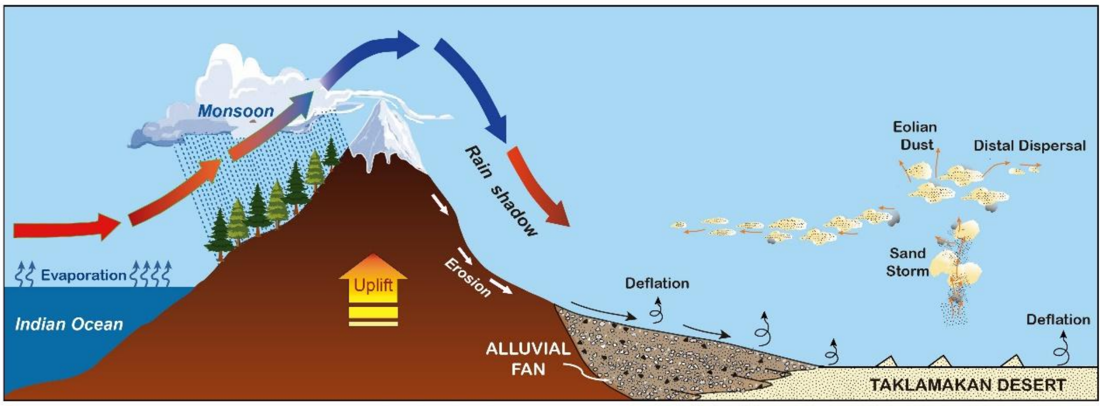

Figure. 8 A schematic diagram deciphering the formation of a ‘rain shadow’ and a ‘dust factory’. A rain shadow is created owing to the uplift of a mountain which has reached a critical height. A dust factory consists of a dynamics chain involving tectonic uplift of a mountain, erosion of bedrocks into sediments, and transportation, sorting and deposition of sediments into deserts and eolian dust. Modifies after [2].

7. Conclusions

The Taklimakan Desert is renowned for being one of the largest deserts and sand seas in the world. Its formation was a significant geological event, not only in Asia but also globally, and its age has been widely debated. Sedimentary sequences within and along the margins of the Tarim Basin, which is presently covered by the Taklamakan, provide crucial information about the desert's evolutionary history. Dating of these sequences suggests that the Taklimakan Desert came into being no later than 25 million years ago. The desert's formation was the result of an extremely arid climate caused by the rain shadow effect and an abundant supply of sediments shed from the mountain fronts. Both of these factors are closely linked to the tectonic uplift of the Tibetan-Pamir Plateau and Tian Shan.

Acknowledgments

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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