WATERFALLS: FORMS, DISTRIBUTION, PROCESSES AND RATES OF RECESSION

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Abstract: A waterfall is a very steep (commonly nearly vertical) fall of some magnitude in a river course. Waterfalls are widespread fluvial landforms that have been described from many parts of the world. Thirty-eight World Heritage Properties include waterfalls in their designation. In addition, some waterfalls are actual or potential geomorphosites. Waterfalls occur in almost all climatic environments, though they are particularly common in formerly glaciated areas. They occur on a huge diversity of rock types, although in general, they do not form persistent or large falls on soft or unconsolidated rocks. Waterfalls also occur in a wide range of geomorphological settings: glaciated areas, areas of active tectonism, areas of sea-cliff retreat and sea-level change, great escarpments on passive margins, basins with river capture, rifted and faulted areas and areas that have been subjected to megaflooding. Multiple processes account for waterfall retreat and varying rates of recession. Although the greatest interest has been in rates of waterfall recession, there are examples of waterfalls that prograde as a result of tufa deposition.

Key words: waterfalls, caprock, knickpoints, plunge pools, tufa

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Introduction

Waterfalls are widespread fluvial landforms that have been described from many parts of the world and have attracted the attention of great geomorphologists such as Charles Lyell, Grove K. Gilbert and William M. Davis. They are currently of great interest because of their scenic and geodiversity value. Waterfalls are also important geomorphologically because they are an extreme manifestation of a knickpoint/channel gradient steepening. That said, as Young (1985) pointed out, they have been the subject of surprisingly limited research. The purpose of this paper is to review such research that has been undertaken, to classify waterfalls, and to try and establish the major factors that have controlled their form, distribution and rates of retreat. Such factors include climatic conditions, rock types, the history of glaciation and of climatic change, and tectonic situation.

These very beautiful features have been described by many travellers and explorers (e.g. Curzon 1923, Rashleigh 1935) and have drawn the attention of poets and artists (Hudson 2012, Hayman 2014, Cole 2015). They have been listed in various popular series (e.g. Reader's Digest 1980, 1993) and on some comprehensive websites (e.g. World Waterfall Database 2018, European waterfalls 2018). Thirty-eight World Heritage Properties also include waterfalls in their designation (WHC 2018) (Table 1). There are also many waterfalls listed in the World Heritage Tentative Lists, including, for example, in the Aberdare

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Table 1. World Heritage Sites with waterfalls included in their designation.

World Heritage Site	Country
Wet tropics of Queensland	Australia
Greater Blue Mountains Area	Australia
Purnulu National Park	Australia
Iguacu National Park	Brazil
Atlantic Forest South East Reserves	Brazil
Central Amazon Conservation Complex	Brazil
Pirin National Park	Bulgaria
Nahanni National Park	Canada
Canadian Rocky Mountain Parks	Canada
Gros Morne National Park	Canada
Mount Huangshan	China
Huanglong Scenic and Historic Interest Area	China
Jiuzhaigou Scenic and Historic Interest Area	China
Wulinghuan Scenic and Historic Interest Area	China
Lushan National Park	China
Mount Sanqingshan National Park	China
China Danxia	China
Cocos Island National Park	Costa Rica
Talamanca Range-La Amistad Reserves / La Amistad National Park	Costa Rica / Panama
Plitvice Lakes National Park	Croatia
Morne Trois Pitons National Park	Dominica
Sangay National Park	Ecuador
Rio Platano Nature Reserve	Honduras
Tropical Rainforest Heritage of Sumatra	Indonesia
Gunung Mulu National Park	Malaysia
Te Wahipounamu – South West New Zealand	New Zealand
West Norwegian Fjords	Norway
Laurisilva of Madeira	Portugal
Putorana Plateau	Russian Federation
Škocjan Caves	Slovenia
Jeju Volcanic Island and Lava Tubes	South Korea
Dong Phayayen-Khao Yai Forest Complex	Thailand
Thungyai-Huai Kha Khaeng Wildlife Sanctuaries	Thailand
Hierapolis-Pamukkale	Turkey
Ruwenzori Mountains National Park	Uganda
Yosemite National Park	USA
Canaima National Park	Venezuela
Mosi-oa-Tunya/Victoria Falls	Zambia and Zimbabwe

Mountains in Kenya and Vatnajökull in Iceland. In addition, some waterfalls are actual or potential geomorphosites, as in India (Kale 2014), Brazil (Santos et al. 2015), Malaysia (Tongkul 2016) and Spain (Ortega-Becerril et al. 2017). In Britain, many waterfalls have been designated as Geological Conservation Review sites and include the following: Alport Valley, Aysgarth, Corrieshalloch Gorge, Falls of Clyde, Falls of Dochart, Grey Mare's Tail, Hepste, Llugwy, Lydford Gorge, Mellte, Rhaeadr and Twymyn (Gregory 1997).

Concerns have been expressed that many impressive waterfalls are being obliterated or diminished by the damming or diversion of rivers, as with the Guairá Falls, located on the Paraná River at the border of Brazil and Paraguay. They disappeared when submerged by dam construction in 1982, after having been one of the most powerful falls in the world (Niland 2017). Likewise, the Ripon Falls at the exit of the Nile from Lake Victoria were effectively eliminated in 1954 by the construction of the Owen Falls dam, while in Norway the flow over the Tyssestrengene Falls, following their use by the Norwegian Hydroelectric Power Authority, has diminished to such a point that only after heavy snow melts is there any flow of substance. Most of the year, there is no water flowing. Likewise, hydropower development threatens Estonia's major waterfall (Ehrlich, Reimann 2010) and has destroyed various waterfalls in Jamaica (Hudson 1999).

Waterfalls have considerable ecological importance, in that they not only act as barriers to the movement of organisms, but also provide specific habitats of conservation value (e.g. Hora 1932, Clayton et al. 2016). Deposits associated with their plunge pools can be used to establish past precipitation events and trends (Nott, Price 1994, Nott et al. 1996).

Definitions and classification by form

Ford (1968: 1219) provided a definition of waterfalls and related phenomena: *A waterfall is a very steep commonly vertical fall of some magnitude in a river course. Cataract is a synonym; cascade describes a fall of only a few feet, or a succession of such falls; rapids are less steep but sufficient to accelerate noticeably the rate of flow and maintain white water at all stages of discharge*. Mabin (2000: 86) also provided a definition: *Waterfall: a vertical or near-vertical fall down a rock face in a watercourse, marked at the top by a clear lip or abrupt steepening in the channel slope. Sometimes a plunge pool may be present. The horizontal distance between the positions of the lip and plunge pool should be no more than c 25% of the waterfall height*. This paper is only concerned with waterfalls *sensu stricto.* Waterfalls have an array of shapes: they may possess overhangs, occur as a series of steps, may have plunge pools, may have broad arcuate shapes (Horseshoe Falls) or may be long and narrow. A classification employed by the National Geographic (2018) divides waterfalls into the following types:

- A *block waterfall* descends from a wide stream
- A *cascade* is a waterfall that descends over a series of rock steps
- A *cataract* is a powerful, even dangerous, waterfall
- A *chute* is a waterfall in which the stream passage is very narrow, forcing water through at unusually high pressure
- *Fan waterfalls* are named for their shape. Water spreads out horizontally as it descends
- *Horsetail waterfalls* maintain contact with the hard rock that underlies them
- *Multi-step waterfalls* are a series of connected waterfalls, each with their own plunge pool
- *Plunge waterfalls*, unlike horsetail falls, lose contact with the hard rock
- *Punchbowl* waterfalls are characterised by wide pools at their base
- *Segmented waterfalls* are where flow separates as distinct streams

There has also been considerable debate as to which waterfalls are the largest, and whether this should be based on the height of the largest vertical fall, the combined height of all falls at a site, the width of the site or the discharge of the flow over the fall (Matthes 1922, Plumb 1993, Mabin 2000). Table 2 lists the world waterfalls in terms of their heights. The world waterfall database documents 949 waterfalls between c. 100 and 1000 m high and ranging in estimated discharge from c. 150 to 42,500 $m^3 s^{-1}$.

Genetic classification

Various schemes have been developed to classify waterfalls both in terms of their characteristics and their origins. An excellent early model on origins was provided by Lobeck (1939: 136) and this is reproduced as Fig. 1.

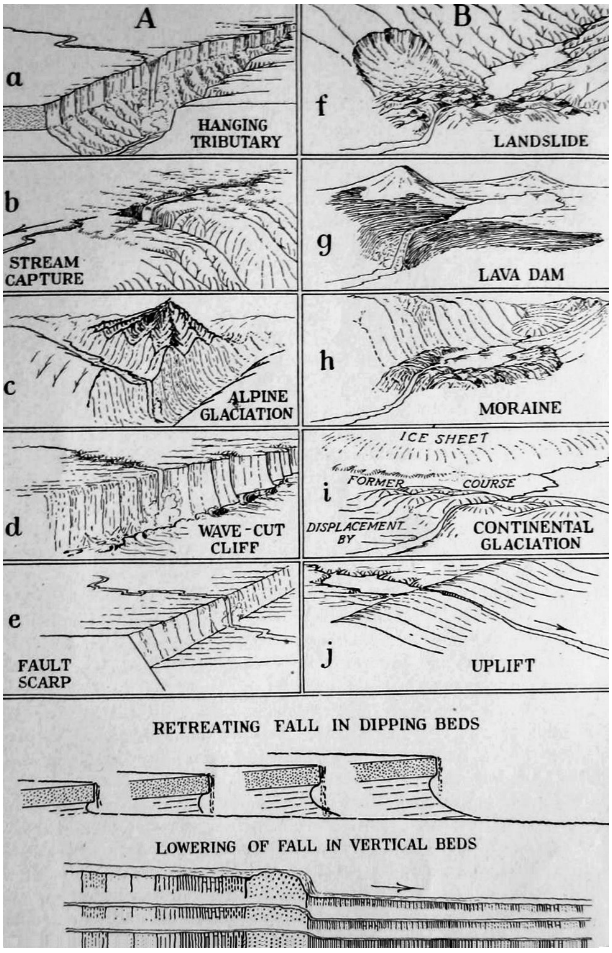

Fig. 1. Lobeck's classification of types of waterfall.

Table 2. Heights of world waterfalls with fall of more than 165 m.

Fall	River	Country	Height of fall (m)	Setting	Geology
Kerepakupi (Salto Angel)	Rio Gauja	Venezuela	807	Plateau edge	Sandstone
Kukenaam, salto	Rio Kukenaam	Venezuela	674	Plateau edge	Sandstone
Ventisquero Colgante	–	Chile	549	Glacial	–
Gocta	Cocahuyaco	Peru	540	Amazonia	–
Ribbon	Ribbon Creek	California, USA	491	Glacial	Granite
Mtarazi	Mtarazi	Zimbabwe	479	Plateau edge	Granite/dolerite
Cerberus	Ice Fall Brook	Canada BC	475	Glacial	Volcanics
Piedra Bolada	Piedra Bolada	Mexico	453	Rift margin	Granite
Yosemite Falls	Yosemite Creek	California, USA	436	Glacial	Granite
Tugela	Tugela	South Africa	411	Plateau edge	Sandstone
Sju Søstre	Knivsflåelvane	Norway	410	Glacial	Misc. crystalline
Blanche	–	Réunion	400	Volcanic	Lava
Churún Vena	–	Venezuela	400	Plateau edge	Sandstone
Castaño Overo	Castaño Overo	Argentina	366	Glacial	Volcanic
El Dorado	Rio Aracá	Brazil	353	Plateau edge	Sandstone
Nohkalikai	Pyjngithuli River	India	340	Plateau edge (horst)	Eocene sandstones
Mardalsfossen	Inste Mardøla	Norway	320	Glacial	–
Skytjefossen	Skytjedalen	Norway	315	Glacial	–
Turner	Cleft Creek	New Zealand	314	Glacial	–
Tyssestrengene	Tysso	Norway	312	Glacial	–
Basaseachic	Basaseachic	Mexico	312	Rift margin	–
Roraima, Salto	–	Venezuela	305	Plateau edge	–
Trou de Fer	Bras de Caverne	Réunion	305	Volcano	Volcanics
Staubbachfall	Staubbach	Switzerland	297	Glacial	Sandstone
Gavarnie	Gave de Pau	France	281	Glacial	Lava
Vetisfossen	Morka-Koldedøla	Norway	275	Glacial	–
Volefossen	–	Norway	274	Glacial	–
Arpenaz	La Laiteuse	France	270	Glacial	–
Sutherland	Arthur	New Zealand	270	Glacial	–
Tueeulala	Falls Creek	USA	268	Glacial	–
Wallaman	Stoney Creek	Australia	268	Plateau edge	–
Parijaro	Rio Alto Cuti-verini	Peru	267	Glacial	–
Kyrfoss	–	Norway	265	Glacial	–
Hunlen	Hunlen Creek	Canada BC	260	Glacial	Limestone
Takkakaw	–	Canada BC	260	Plateau edge	Quartzite and conglom-erate
King Edward VIII	Semang	Guyana	256	Plateau edge	–
Jog	Saravati	India	253	Plateau edge	Banded gneiss
Skrikjo	Skrikjo	Norway	250	Glacial	–
Gjerdefossen	Ktituervla	Norway	245	Glacial	Sandstone and con-glomerate
Kaieteur	Potaro	Guyana	226	Plateau edge	Metasediments
Wollomombi	Wollomombi	Australia NSW	224	Plateau edge	Sandstone, quartzite and shale
Kalambo	Kalambo	Zambia and Tanzania	221	Rift edge	Sandstone, quartzite and shales
Tad Fane	–	Laos	213	Plateau edge	–
Kjerrskredfossen	Kjelfossgrovi	Norway	206	Glacial	
Kjelfossen	–	Norway	198	Glacial	
Bridalveil	Bridalveil Creek	California, USA	189	Glacial	
Drury Falls	Fall Creek	USA	183	Glacial	
Svøufallet	Grødola	Norway	167	Glacial	
Serio	Serio	Italy	166	Glacial	
Multnomah	Multnomah Creek	Oregon, USA	165	Missoula floods hanging valley	Basalt

Distribution

Climate

Waterfalls occur in almost all climatic environments. In terms of negative factors, they are scarce in many arid areas because of a lack of stream flow; but even here, extreme rainfall events and past pluvial episodes may explain the existence of *dry waterfalls* in the Eastern Desert of Egypt (Sandford 1928), and Hume (1925: 88 and plate XLIV) gives a very clear illustration of this. The waterfall on the edge of the Namib Desert at Etusis in central Namibia only flows in exceptionally wet years (see Fig. 7).

In terms of positive factors, they are common in formerly glaciated areas such as Norway, the European Alps and the South Island of New Zealand because of the creation of hanging valleys by glacial erosion or because of glacial diversion of drainage. It was also postulated by Birot (1968), Büdel (1982) and Tricart (1965) that they and cataracts were common in humid tropical areas because of the fact that deep weathering meant that there was a shortage of coarse sediment in stream courses to cause removal of irregularities. Subsequent research has thrown doubt upon the generality of this supposition (Ollier 1983).

Rock types

Introduction

Waterfalls occur on a huge diversity of rock types, although in general, they do not form persistent or large falls on soft or unconsolidated rocks. Table 2 suggests that they may be especially common on bedded sandstones and on basaltic lavas. However, they also occur *inter alia* on granites (Chisholm 1885), gneiss, schist, limestones, dolomites, quartzites and conglomerates.

The caprock model

The most venerable model for waterfall development with respect to rock type is the so-called caprock model that was described by Lyell (1845) in the context of the Niagara Falls. Lyell (1875: 355, 356) remarked that the uppermost rocks of the Falls consist of hard Silurian limestone around 30 m thick, *beneath which lie soft shales of equal thickness, continually undermined by the action of the spray, which rises from the pool into which so large a body of water is projected and is driven violently by gusts of wind against the base of the precipice. In consequence of this action, and that of frost, the shale disintegrates and crumbles away, and portions of the incumbent rock overhang forty feet, and often when unsupported tumble down, so that the Falls do not remain absolutely stationary at the same spot, even for half a century*. This model was accepted by Geikie (1893) and Gilbert (1895). Likewise, Cotton (1941: 32) reported that *Falls, as distinguished from rapids, are developed by vertical corrosion where rivers cross the edges of outcropping strata of resistant rock, and especially where these are horizontal or only gently inclined, and where they overlie weak materials. The resistant beds, or fall markers, may be lava flows or indurated sedimentary strata*. He gave the example of the Wairua Fall of the North Island of New Zealand, formed where the river has cut down through lava that had invaded the floor of its former valley. *The lava rock itself, though free from joint cracks and resistant to erosion in its surface layer, is weakened below by the presence of tension joints due to shrinkage during cooling, the result being effective undermining of the edge of the superficial strong layer by plunge-pool erosion* (Cotton 1941: 32, 33). The model has also been applied to High Force in northern England, where the River Tees falls over an outcrop of the dolerite Whin Sill, which lies above the softer Carboniferous limestone (Goudie and Gardner 1985: 18).

The caprock model is not of universal applicability as pointed out by Young (1985). Young et al. (2009: 202–204) wrote: *The widespread occurrence of major waterfalls on sandstones is normally attributed to the undercutting of a caprock by the disintegration of a softer rock beneath it*. However, *instead of being undercut, many waterfalls in sandstones are buttressed at the base, and some even lack plunge pools*. They believed that *the basic requirement for the development of waterfalls appears to be the outcrop of rock that, because of its lithological and structural properties, will stand in a steep face. Basal undercutting may certainly promote the development of a steep face, but it is not an essential requirement*. Moreover, as Von Engeln (1942) and others have pointed out, horizontal strata are not a *sine qua non*, for *vertical barrier falls* result from the presence of a barrier (e.g. of lava). Some of the greatest waterfalls, including the Victoria Falls and the Iguazu Falls, occur in tick basalt sequences, and the caprock model does not apply to them.

Examples of the relationship between rock type and fall development

In this section, the links between rock type and water fall development are explored in the context of specific regional sites.

USA. Worcester (1939) stressed the importance of lavas as on the Shoshone, Twin and American Falls on the Snake River in Idaho, USA. Ray and Rahn (1997) looked at the waterfalls of Black Hills, Dakota. These are developed on Precambrian metamorphic and igneous rocks. Tarr (1905) described many waterfalls in central New York State associated with Devonian sandstones overlying shales.

South America. In South America, the great Iguazu Falls (Fig. 2) and others in the Parana basin (Lima and Binda 2013) have developed over Cretaceous basalts laid down across sandstones, while in Venezuela, some of the tallest falls in the world have developed over sandstones. In Amazonas (Brazil), falls have developed in quartz arenites (Nogueira et al. 2001), while in the Pernambuco area of northeast Brazil, falls have developed in Neoproterozoic granites, granodiorites and orthogneisses.

Africa. In South Africa, Norman and Whitfield (2006) noted that in the east of the country, the Mgeni River plunges over Howick Falls, a precipitous 95 m drop over a resistant dolerite sill that intruded Ecca shales. Waterfalls are associated with the Great Escarpment as near Sabie – Horseshoe Falls, Lone Creek Falls (68 m) and Bridal Veil Falls (70 m). All owe their existence to rapidly eroding streams in the Sabie valley meeting with hard quartzites at the upper contact of the Malmani dolomite and the overlying Pretoria Group. Also, close to Sabie are the MacMac Falls (56 m high), the Lisbon Falls (92 m) and the Berlin Falls (150 m), which result from streams falling off platform-like Black Reef quartzites. The 145-m tall Augrabies Falls on the Orange River have formed in granite-gneiss (Tooth 2015) (Fig. 3).

Fig. 2. The Iguazu Falls on the border of Argentina and Brazil. Photo courtesy of Alice Goudie, April 2013.

Fig. 3. The Augrabies Falls on the Orange River, South Africa. Photo: July 1968.

Fig. 4. The Victoria Falls from the Zimbabwe side. Photo: August 1993.

Further north, the Victoria Falls on the Zambezi are formed in Jurassic (Karoo-age) basalts (Clark 1952, Moore and Cotterill 2010) (Fig. 4). In Guinea, dolerite and gabbro sills are the cause of several waterfalls, where they form hard rock outcrops along river beds in the Fouta Djallon (e.g. the Kinkon Falls) (Buckle 1978: 54).

Australasia. In Australia, many of the waterfalls have developed in sandstones, as with the waterfalls of the Kimberley, which fall over Proterozoic rocks (Fig. 5). Seidl et al. (1996) noted that in southeastern Australia, on the New England Tableland, many waterfalls had formed in Paleozoic fine-grained meta-sedimentary rocks, as at Wollomombi, though some occurred in Late Carboniferous granites. Other falls in New South Wales have developed in rhyolites (Bishop and Goldrick 1992). In New Zealand, falls on the Waipaoa River in the North Island are formed on Cretaceous to Pliocene shelf and slope sediments (siltstones, mudstones and sandstones) (Crosby and Whipple 2006), while the Taranaki Falls are at the edge of an old lava flow. The Waipunga Falls, further east, flow over ignimbrite rock deposited in the 200 AD Taupō eruption. Both the Wairua Falls in Northland and the Bridal Veil Falls near Raglan drop over old basalt lava flows (Manatū Taonga MCH 2018).

*Asia and Pacific Basin***.** In India (Kale 2014), the Nohkalikai Falls on the Pyjngithuli River over the Meghalaya Plateau have a sheer drop of c. 198 m and have formed on the Eocene sandstones of the Cherra Formation. The Gersoppa or Jog Falls (c. 253 m high) occur on the Sharavathi River in Karnataka, where it leaps over the Western Ghats. It is underlain by banded gneisses. In Korea, Migoń et al. (2018) describe waterfalls developed in granites, while in northeast China, waterfalls have developed on volcanic rocks (Zhang et al. 2011) and on the limestones of the Yunnan–Guizhou Plateau (Hankui et al. 1984). The waterfalls of Central Vietnam are developed in basalt (Phuong et al. 2017). In the Pacific Basin, waterfalls are present on young volcanic rocks as in Japan (Hayakawa et al. 2008, Yoshida et al. 2017), Hawaii (Mackey et al. 2014) and French Polynesia (Ye et al. 2013).

Europe. In Poland, Alexandrowicz (1994) found that in the case of the Polish Outer Carpathian Mountains, small waterfalls developed on Flysch sandstones, while in the Czech Republic, many waterfalls in the Jizerské Hory region are formed in granites (Migoń 2016). In Iceland, waterfalls are formed in columnar basalts of relatively recent age, associated with mid-Ocean sea floor spreading (Schwarzbach 1967, Baynes et al. 2015) In Scotland, the falls in the Corrieshalloch Gorge are formed in Moine schists, the Falls of Clyde and the Grey Mare's Tail in greywacke sandstones, and the Falls of Dochart in schist. In

Fig. 5. The King George Falls, Kimberley, Western Australia. Photo: August 2017.

Wales, the Afon Rhaeadr Falls are developed in Ordovician slates, the Trymyn Falls in Silurian sandstones and the Hepste Falls and Mellte Falls also in sandstones. In England, the Lydford Gorge waterfall is formed in slates, High Force is on a dolerite sill overlying softer Carboniferous limestone and the Aysgarth falls on limestone interspersed with shale beds (Gregory 1997).

Many waterfalls occur in areas with lithological contrasts. Bloom (1998: 258) referred to this in the context of the Fall Line in the eastern USA: *Such an erodibility contrast is to be seen in the eastern United States along the Fall Zone – a seaward dipping exhumed erosion surface between crystalline rocks of the Piedmont and New England Provinces and the overlying coastal plain sediments of Cretaceous and younger ages. Post-orogenic erosion created this surface of low relief before it was buried by onlapping marine sediments. Subsequent gentle epeirogenic warping has uplifted the landward region and depressed the seaward part so that a narrow bevel or facet of older metamorphic rocks has been exposed on the inland edge of the coastal plain by erosion of the former cover strata. The steepened gradients and many waterfalls on rivers where they cross the Fall Zone gave the region its name*.

In general terms, rock joint and fracture characteristics are a significant control of fall morphology (Scott and Wohl 2019), and resistance and bed disposition affect the nature and location of step-pool sequences (Wohl 2000). Ortega et al. (2013) studied waterfalls in the Rocky Mountain National Park in Colorado, USA. They found that the shape of individual waterfalls and their height of drop correlated well with bedrock properties. Waterfalls in bedrock lacking vertical joints perpendicular to flow are more likely to have a single drop rather than multiple drops, and taller waterfalls correlate with more widely spaced horizontal joints or bedding planes. Likewise, Lima and Flores (2017) found that significant differences in the vesicularity and jointing of basaltic flows influenced the form of knickpoints in Parana basalts in Brazil. The role of stress relief and the associated development of vertical jointing also need to be considered (Lee 1978).

Geomorphological settings

Waterfalls occur in a wide range of geomorphological settings, as indicated in Lobeck's diagram in Fig. 1. A similar list of settings was also provided by Buckle (1978: 110–111) who suggested that the following are the main causes of waterfalls:

- an outcrop of hard rock overlying softer rocks in the river bed,
- faulting across the river bed,
- where the river enters the sea at a cliff line following erosion or where sea level has fallen,
- where a tributary hanging valley enters a glacially over-steepened major valley,
- a lava or landslide may create a lake and a waterfall that occurs where overspill drops over the edge of the barrier,
- where a river falls over a plateau edge,
- where rejuvenation of a river valley has formed a sharp knickpoint.

Waterfalls can also occur where tectonic uplift of the entire river network is too rapid for smaller streams to respond, so tributaries can become very steep or have convex longitudinal profiles, as well as a waterfall at the main channel junction.

Stage of valley development

In the era of cyclic and evolutionary geomorphology, Davis (1884) doubted that falls would develop in catchments that had reached a state of maturity and averred that waterfalls are seldom found in *old countries* of flat rocks and moderate elevation. As Lobeck (1939: 197) recognised: *Waterfalls and rapids are criteria of youth. There are two kinds: first, those which develop in the normal life history of a river and indicate that the stream has not yet acquired a graded slope; and, second, those which result from some disturbance, accident, or interruption in the life of the stream, imposed upon it by some outside force*.

Rift valley and fault development

Major changes in base level with rift valley development provide ideal conditions for waterfall development. The classic example of this is provided by the Kalambo Falls at the border of Zambia and Tanzania (Buckle 1978). The Murchison Falls on the Nile occur where the river plunges over the pelitic schists of the Western Rift (Wolman and Giegengack 2008). Vertical waterfalls also occur along the Dead Sea Rift in Israel in a dolomite caprock with underlying, marly-limestone footrock (Enzel et al. 2005, Haviv et al. 2010). Malatesta and Lamb (2017) noted than in

California, waterfalls commonly occur near the bounding faults of mountain ranges. Working in Death Valley, they found that incision of alluvial fans, resulting from climatic and tectonic forces, can expose waterfalls. Surface ruptures along the Chelungpu thrust fault in west-central Taiwan caused formation of knickpoints and small waterfalls according with bedrock exposure in riverbeds when the 921 Chi-Chi Earthquake occurred on September 21, 1999 (Hayakawa et al. 2009, 2010). Waterfalls also occur across the Main Boundary Thrust zone of the sub-Himalayas in northern India (Kothyari et al. 2010) and the Trans Himadri Fault of the Kumaun Tethys Himalaya (Kotlia, Joshi 2013).

Areas of sea-cliff retreat and sea-level change

Rivers in areas of tectonic uplift may not be able to cut down sufficiently quickly to have smoothly graded courses, and so may have knickpoints (Jansen et al. 2011) or may cascade over cliffs producing waterfalls. An example of this is provided by the coastline of California (Limber, Barnard 2018). Here, there is an active margin shoreline characterised by uplift, cliff retreat and river incision, with consequent formation of waterfalls. In Hawaii, the Ka'ula'ula waterfall has migrated backwards over the past 120 ka. It is a knickpoint that was initiated by sea-cliff erosion at a time of high sea level during the last interglacial (Mackey et al. 2014). In Tahiti, Ye et al. (2013) suggested that a sudden drop of sea level followed by cliffing created knickpoint conditions that led to waterfall formation. Waterfalls caused by cliff retreat and the creation of hanging valleys are also a feature of the north coasts of Devon and Cornwall in southwest England (Arber 1911).

The glacial impact

Waterfalls are widespread in areas that were glaciated in the Pleistocene. Notable here are the waterfalls that cascade down the sides of fjords in Norway and New Zealand (Fig. 6) and of glacial troughs in the European Alps (Hayakawa

Fig. 6. Waterfalls in the glacially overdeepened fjord of Milford Sound, New Zealand. Photo: August 1989.

2011), the Pyrenees (Ortega-Becerril et al. 2017) or the flanks of Yosemite in the USA (Waltham 2012). These result from the formation of hanging valleys and overdeepened trunk valleys. However, in addition, as Russell (1898: 61) pointed out, *many of the falls in the drift-covered region of North America are due to the turning of streams from pre-glacial valleys in such a way as to cause them to flow over what were formerly divides or rocky spurs between adjacent streams and plunge into valleys*. Great Falls, Connecticut, is an example of a feature created by such glacial activity. Waterfalls can occur on cirque headwalls, where these undercut pre-glacial plateaus – like these in the Karkonosze Mountains of Poland.

Landslide and lava dams

Large rockfalls and landslides can dam stream channels, leading to the development of lakes from which outflow may occur in the form of a waterfall over the downstream face of the deposit. This was recognised as a waterfall type by Lobeck (1939), as shown in Fig. 1, but relatively little work has been conducted on them. However, examples are known from steep mountain ranges, particularly in areas with seismic activity, as with the Karakoram Mountains. Wang et al. (2014) discuss this in the context of the Wenchuan earthquake in China in 2008.

Lava dams can block rivers, and thereby create lakes and waterfalls. Examples of this are known, for example, from the San Francisco Volcanic Field in Arizona (Plescia 2008), the North Island of New Zealand (Cook et al. 2018) and the Kegon Falls of Japan (Hayakawa 2013).

Great escarpments on passive margins

Some continental margins are lined by great escarpments that have developed on passive plate margins and which may have become elevated, at least in part, by faulting, thereby promoting river incision and gorge development. This is the case with eastern Australia (Seidl et al. 1996, Weissel and Seidl 1997), the Western Ghats of India (Kale 2010), the Serra do Mar in Brazil (Stevaux, Latrubesse 2010) and the western and eastern margins of southern Africa. In the last case, falls are notable on the Kunene River (at Ruacana), on the Orange (at Augrabies) and on the Tugela.

As escarpments retreat, streams on the plateau top may have their catchment areas and flows reduced, while streams eating backwards have their drainage areas and flows increased. This means that the former become less powerful, while the latter become more powerful. This can lead to an acceleration of gorge incision (Berlin, Anderson 2007). The smaller drainage catchments become unable to keep up with the incision of the main stream, and so steep knickpoints and hanging valleys develop (Crosbie, Whipple 2006, Wobus et al. 2006).

River capture and rejuvenation

Any change in relative base level, which might not involve river capture, sea-level change or glaciation, has the potential to result in headward migration of knickpoints. This was demonstrated in the context of the Colorado Front Range by Anderson et al. (2006). However, river capture can lead to base level changes that are conducive to stream incision and waterfall development. For instance, a possible explanation for the development of the Victoria Falls is that the Upper Zambezi was captured by a headwater tributary of the middle Zambezi relatively recently in the late Cenozoic. The rapid headward erosion of the Batoka and higher gorges towards the falls would have been initiated by the marked lowering of base level following the capture (Moore, Cotterill 2010). River capture has also been implicated in the development of falls across the Kunene River at Epupa and Ruacana in Namibia/Angola (Kanthack 1921, Wellington 1955: 65). In Britain, the Lydford Gorge Falls are a classic example of the role of river capture (Gregory 1997).

Areas subject to megaflooding

It is possible that some gorges and amphitheatrical valley heads, which become the sites of waterfalls, were initiated by past megafloods. Lamb and Dietrich (2009) postulated that this was the case in the volcanic terrains of NW USA, where catastrophic floods (e.g. the Bonneville Flood) have carved steep, blunt-headed canyons in columnar basalt. Likewise, Lamb et al. (2014) argued that the Malad Gorge in Idaho, which has been cut into columnar basalt, was not caused by normal fluvial erosion or by groundwater seepage. Rather, it was due to a megaflood at 46 ka when lava flows dammed the Wood River, resulting in outburst flooding. The glacial Lake Missoula floods generated huge waterfalls, such as the Palouse Falls in Washington State (Waltham 2010), and breaching of a chalk barrier in what is now the English channel by overflow from a proglacial lake created enormous waterfalls (Gupta et al. 2017). Waterfalls associated with glacial megafloods are also known from NW Germany (Meinsen et al. 2011) and the Altai Mountains of Siberia (Rudoy 2002). Large floods in the Holocene have greatly influenced canyon evolution in Iceland (Baynes et al. 2015), and massive glacial floods may have contributed to the formation of large waterfalls in the Tsangpo Gorge in Tibet (Montgomery et al. 2004). Floods derived from caldera breaching have caused waterfalls in northern Japan (Kataoka 2011). Some falls that are currently largely dry may have been subjected to much larger flows in the Pleistocene, as was the case with the so-called Dry Falls in Washington State and with Malham Cove in Yorkshire, England, though it turned into a waterfall for the first time in living memory during the exceptionally wet winter of 2015/2016 (McCarthy et al. 2016).

Processes operating to cause waterfall recession

In the original caprock model, Lyell (1875) mentioned the role of both spray and frost weathering of shale in causing waterfall recession. Bishop and Goldrick (1992) believed that failure at joint planes along the lip of falls seems to be the major cause of retreat in two examples from New South Wales. They noted that potholes, perhaps caused by cavitation, drill down from above.

Haviv et al. (2006, 2010) also stressed the role of gravitational failures, direct abrasion by the falling jet, direct abrasion by plunge pool rollers, wet–dry weathering, frost attack and seepage weathering. Similarly, Hayakawa (2013), working in Japan, recognised the importance of multiple processes accounting for retreat, including rockfalls, surface water free fall load, freeze–thaw or wet–dry weathering and cavitation at the lip of the falls. Cavitation may indeed be an underestimated cause of bedrock erosion (Whipple et al. 2000). Lamb and Dietrich (2009) argued that although many people have proposed that waterfalls retreat by undercutting, many propagating waterfalls maintain a vertical face in the absence of undercutting. They stressed that vertical waterfalls can remain vertical in retreat due to toppling in bedrock with near-horizontal and vertical sets of joints. At a waterfall, faces are affected by shear and drag from the overflowing water, buoyancy from the plunge pool at the base of the waterfall and gravity. They also suggested that although seepage erosion has been proposed as an alternative to plunge pool erosion, the evidence for seepage flow is ambiguous and cannot generally explain the excavation of coarse collapsed debris. Likewise, Lamb et al. (2007) believed that in Hawaii, surface runoff rather than seepage carves amphitheatrical headed valleys. Plunge pool erosion by powerful streams with relatively large catchments and their sediment load leads to steep waterfalls, though jets of high-velocity water can cause clear water erosion (Pasternack et al. 2007). Lapotre and Lamb (2015) also believed that flow acceleration means that flow erosion is accelerated at the brink of a waterfall and thus promotes plucking and toppling of jointed rock. Plunge pools, the character of which is affected by factors such as flow velocities, sediment supply and grain sizes, are significant components of waterfall systems (Elston 1917, Scheingross, Lamb 2016), and the work of Scheingross, Lamb (2017) pointed to the importance of vertical drilling of successive plunge pools for propagation of upstream migration rather than the undercutting model. However, Scheingross et al. (2019: 229) proposed that *waterfalls can form autogenically, meaning that waterfalls can form through internal feedbacks between water flow, sediment transport and bedrock incision, in the absence of external perturbations or lithologic controls*.

Fig. 7 shows a large plunge pool at the base of a dry waterfall formed in quartzite at Etusis, central Namibia. Pothole erosion is also an important process at the Augrabies Falls (Springer et al. 2006). There is now a large literature on the factors affecting the development of plunge

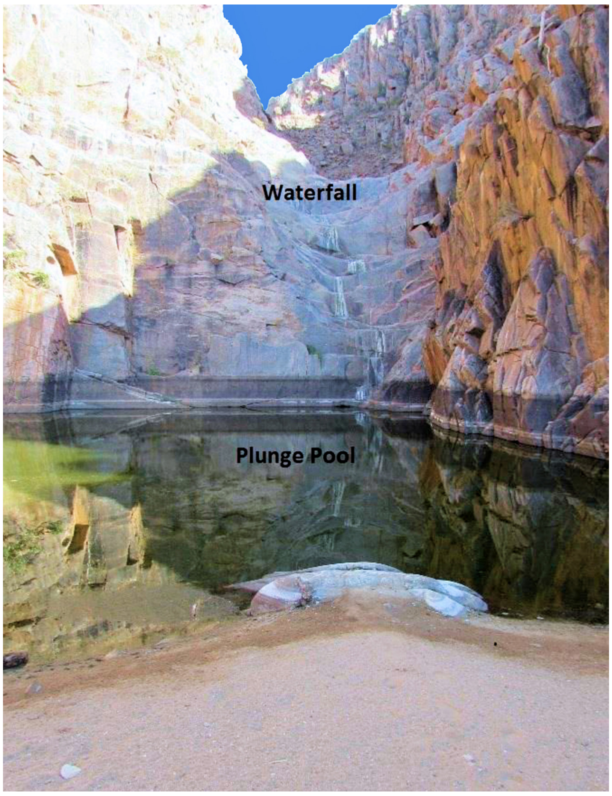

Fig. 7. A *dry waterfall* developed in Neoproterozoic metaquartzites at Etusis, central Namibia, with a water-filled plunge pool at its base. The mean annual rainfall at this site is only c. 240 mm per year. Photo: September 2018.

pools beneath artificial dams, and this may provide insights into the development of natural plunge pools (e.g. Melo et al. 2006, Fiorotto et al. 2016).

Rates of waterfall recession

Not all waterfalls will necessarily undergo recession at any appreciable rate. As Lake (1925: 249) stated: *Whenever a waterfall cuts backwards there will usually be a gorge below it, for the backward erosion is generally rapid compared with the lateral erosion of the sides of the valley. But there are cases in which there is scarcely any backward erosion at all. If a hard bed, or an igneous dyke, runs vertically across the river, the soft rock on the down-stream side will be rapidly worn away and a waterfall will be formed. But no undermining of the hard bed is possible*.

Furthermore, rates of waterfall recession will vary in time. For example, retreat may be rapid after a fault causes a fall to develop across a watercourse. This was the case in Taiwan (Hayakawa et al. 2010). Surface ruptures along the Chelungpu thrust fault caused formation of waterfalls when the 921 Chi-Chi Earthquake occurred on September 21, 1999. Since then, they have receded upstream at extremely rapid rates, causing bedrock incision for tens to hundreds of metres in length within a decade. Field measurements revealed that the mean rate of a knickpoint recession in the largest river (Ta-chia) was 3300 mm per year in the earlier 6 years (1999–2005) and 220,000 mm per year in the last 4 years (2005–2009). This acceleration of the recession may have been due to an increase in flood frequency and intensity, narrowing of the channel width and/or anisotropy of rock strength sandstones and mudstones along the stream. The other knickpoints in the area showed relatively similar recession rates throughout the decade on the order of 20,000–60,000 mm per year.

Another cause of changes in rates of recession through time is the changes in stream discharge and abrasive sediment transport. For example, depletion of paraglacial sediment supply during the Holocene can lead to a deficiency in tools for bedrock erosion.

Dating of landforms and archaeological sites enables estimates to be made of the long-term rates of recession. In the case of the Victoria Falls, Moore and Cotterill (2010) estimated that the rate of recession up the Batoka Gorge was between 42 and 80 mm per year, implying that headward erosion has incised 20 km of gorges below the falls in c. 300–250 ka. Derricourt (1976), also working on the Victoria Falls, used archaeological data to estimate the rates of retreat and suggested a rate of 150 mm year over 20,000 years.

Berlin and Anderson (2007) showed that Late Cenozoic incision of the Colorado River led to isolation of the Roan Plateau in SW USA. This initiated knickpoints and a wave of erosion, with the knickpoint recession rate being a function of drainage area and rock susceptibility to erosion. Knickpoint recession speeds declined through time as catchments became smaller – they started at c. 7.1–11.9 mm per year and have now dropped to 0.3–2.3 mm per year.

Other long term rates have been estimated for glaciated valleys (Hayakawa 2011). The author found that recession rate since deglaciation depends on the erosional power of streams and bedrock resistance. Examples were given from Yosemite and the Swiss Alps. For Lower Yosemite (100 m high), the rate was 46 mm per year; for Isola (60 m high), the rate was 55 mm per year; and for Sils (50 m high), the rate was 75 mm per year. Hayakawa and Wohl (2006) studied the 12-m-high Poudre Falls of the Rocky Mountains Front Range in Colorado. Developed in granite, they had recessed by over 1000 m (90 mm per year) over the 12,000 years since glaciers had retreated from the valley. Sardeson (1908) studied the St Anthony Falls on the Mississippi River and estimated a post-glacial rate of recession of c. 744 mm per year.

In the basalts of the Golan Heights of Israel, the back erosion of the Sa'ar river falls over a period of 100,000 years was 0.68 mm per year (0.68 km) (Shtober-Zisu et al. 2018). In the volcanic terrains of Japan, Hayakawa et al. (2008a) found that the rate of recession, based on the age of ignimbrites, was 13–68 mm per year for the Aso volcanic area, where the height of falls was 8.3–63.3 m. They found that the recession rate depends on discharge, width and height of the fall and on the rock strength (both of which can be estimated). Hayakawa et al. (2008b) studied the 322-m-high Shomyo Falls of central Japan, which had formed in pyroclastic materials of known age. Their estimated rate over 100,000 years was 80–150 mm per year, whereas the current modelled rate using the force/resistance (F/R) index (described below) was only 6–11 mm per year. They believed that this may be due to reduced post-glacial sediment loadings and flow. Hayakawa (2013) estimated the retreat rate for the 98-m-high Kegon Falls, which had developed in andesitic lava since c. 20,000 BP, was 18 mm per year. He noted, however, that a single large rockfall in 1986 led to a recession of c. 8 m. Hayakawa and Matsukura (2003) examined the Beso Falls in Japan. Developed in mudstones, and with heights of 1.8–32 m, rates ranged from 13 to 270 mm per year. Yoshida et al. (2017) studied waterfalls in southern Kyushu, which had developed in ignimbrites100 ka old. The estimated recession rates for six falls (c. 20 m high) were 2–30 mm per year. Mackey et al. (2014) used cosmogenic dating of the Ka'ula'ula waterfall on Hawaii. This has migrated backwards at a rate of 33 mm per year over the past 120 ka.

The rate of retreat of the Niagara Falls has been studied for a long time (Philbrick 1970, 1974, Tinkler 1987, Tinkler et al. 1994, Pryce 1995). Gilbert (1895) calculated a Holocene recession rate of 4–5 feet (c. 1200–1500 mm) per year. Hayakawa and Matsukura (2009) found that the rate of retreat had declined from c. 1000 mm per year a century ago to c. 100 mm year at present. This was due partly to water abstraction by humans, and partly to a natural increase in waterfall lip length. Stevaux and Latrubesse (2010) estimated that the great Iguazu Falls have retreated upstream at a rate calculated to be c. 14–21 mm per year (21–42 km) over the last 1.5–2.0 million years.

Table 3. Rates of waterfall recession ordered according to the rate in millimetres per year.

Location	Source	Rate
Golan Heights, Israel	Shtober-Zisu et al. (2018)	0.68
Roan Plateau	Berlin, Anderson (2007)	0.3–11.9
Kyushu, Japan	Yoshida (2017)	2–30
Aso, Japan	Hayakawa et al. (2008a)	13–68
Iguazu	Stevaux, Latrubesse (2010)	14–21
Beso, Japan	Hayakawa, Matsukura (2003)	13–270
Kegon, Japan	Hayakawa (2013)	18
Hawaii	Mackey et al. (2015)	33
Victoria Falls	Moore, Cotterill (2010)	42–80
Yosemite	Hayakawa (2011)	46
European Alps	Hayakawa (2011)	55–75
Shomyo, Japan	Hayakawa et al. (2008b)	80–150
Poudre Falls, USA	Hayakawa, Wohl (2006)	90
Victoria Falls	Derricourt (1976)	150
Niagara	Hayakawa, Matsukura (2003)	100–1000
St Anthony Falls, USA	Sardeson (1908)	744
Niagara	Gilbert (1895)	1200–1500
Taiwan	Hayakawa et al. (2010)	3300–220,000

The above data are summarised in Table 3. There is a great spread of values, but a characteristic rate appears to be a few tens of millimetres per year.

Causes of variability in waterfall recession rates

Hayakawa and Matsukura (2003) found in their study of the Beso Falls of Japan, there was a good correlation of recession rates determined from the landform ages with an F/R index. This is based on annual precipitation, width and height of fall, water density and rock strength obtained by Schmidt hammer:

$$F \propto (\rho, A, P, W, H),$$
$$R \propto (S_c),$$
$$\frac{F}{R} = \frac{AP}{WH}\sqrt{\frac{\rho}{S_c}},$$

where:
- *A* – the area of catchment upstream of waterfall,
- *P* – the precipitation,
- *W* – the width,
- *H* – the height,
- *ρ* – the density of water
- S_c – is the strength of rock.

DiBiase et al. (2015) argued that the primary controls on waterfall retreat rates are rock strength, joint orientation, coarse sediment supply and water discharge. Coarse sediment abrades waterfall lips, drills plunge pools and erodes non–waterfall-intervening stretches.

Shelef et al. (2018) were of the opinion that waterfall recession rates are controlled by a large range of factors, including plunge pool drilling, freeze–thaw and wet–dry cycles and groundwater seepage. The intensity of these processes depends on factors such as caprock and sub-caprock strengths, joint density, sediment concentration and grain size distribution, water discharge, the micro-topography of the waterfall lip, waterfall height, water jet impact angle and the properties of the lag debris.

Some studies have found a correlation between drainage area and recession rates (Crosby, Whipple 2006), but this is not universally the case (Mackey et al. 2014, Baynes et al. 2018).

Constructive waterfalls

Although the greatest interest has been in the rates of waterfall recession, there are examples of waterfalls that prograde, such as those on the Dunn's River in Jamaica. These are the waterfalls

Fig. 8. Constructive waterfalls in Namibia: (A) in Quiver Tree Gorge in the Namib Naukluft Park and (B) at Blasskrantz. Photos: August 1993.

which were described by Gregory (1911) as *Constructive Waterfalls*. He gave examples from the limestone regions of the Balkans: the Kerka Falls in Dalmatia and the Pliva Falls and Topolje Falls in Bosnia. They are formed by the accumulation of freshwater carbonate drapes, called tufas (Viles, Goudie 1990). Von Engeln (1942) described such falls as *autoconsequent*.

Subsequently, constructive waterfalls have been recorded from many areas, both wet and dry, including the Naukluft National Park in Namibia (Viles et al. 2007, Goudie, Viles 2015), where at Blasskranz, one tufa cascade is some 80 m high and 400 m wide (Fig. 8). Other studies of tufa waterfalls include those of Dramis and Fubelli (2015) in Ethiopia, Wright (2000) in the Kimberley District of northwestern Australia, Zhang et al. (2001) in China, Pawar et al. (1988) in India, Marker (1971) in South Africa, Sanders et al. (2006) in the European Alps, Donovan et al. (1988) in Oklahoma, USA, Ray and Rahn (1977) in South Dakota, USA, Harbor et al. (2005) in the Central Applachians, USA, Travassos et al. (2016) in Brazil, Bonacci et al. (2017) in Croatia, Ukey and Pardashi (2019) in the Deccan of India and Edgell (2006) in southern Oman (e.g. Wadi Darbat). Small waterfalls may also be associated with silica-depositing springs, as in New Zealand (Migoń, Pijet-Migoń 2016).

Conclusions

Waterfalls are both numerous and widespread, and they occur on a large range of rock types and under many different climatic and geomorphic conditions. They are moulded by a range of processes, including the undercutting of a caprock, plunge pool incision, toppling and various types of weathering. Many estimates have now been made of their rates of recession over different timescales, though some waterfalls – constructive waterfalls – may be characterised by aggradation and progradation. Waterfalls are geomorphologically important because, *inter alia*, they are a form of base level adjustment that can strongly influence the rate of landscape evolution throughout drainage systems.

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