A guide to the geology of Alaska and Yukon

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WALTHAM, T. 1995. A guide to the geology of Alaska and Yukon. *Proceedings of the Geologists' Association*, **106**, 313–332. Alaska is a magnificent wilderness which offers dramatic landscapes and varied geology. It lies on an active convergent boundary zone of accreted terranes where fold mountains and volcanoes dominate glacial and periglacial environments. An itinerary follows the route of the 1994 excursion to the finest of Alaska's geological sites. Descriptions include Glacier Bay, the Yukon Valley, the Klondike goldfields, the interior tundra, sites along the oil pipeline, Columbia Glacier, Anchorage, Denali, Kenai Fiords, Katmai and the Valley of Ten Thousand Smokes.

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1. INTRODUCTION

The physical geography of Alaska and Yukon is dominated by the huge mountain chains which wrap around the southern coast of the whole Alaskan peninsula; these are a northern extension of the great Cordillera including the Rockies of the USA and British Columbia. They rise to many summits of over 4000 m in the St Elias Range along the coast between Juneau and Valdez, while Mt McKinley (Denali) reaches 6194 m in the parallel Alaska Range not far inland. North of the Alaska Range, a huge interior basin is drained by the Yukon River, all the way from the British Columbia border out to the west coast of Alaska. Beyond the great river lies the real wilderness of birch taiga and treeless tundra, where the rounded mountains of the Brooks, Ogilvie and Mackenzie Ranges drain north to the Arctic Ocean.

Geological history of Alaska

The geology of Alaska is essentially the product of convergent plate boundary activity and terrane accumulation, all complicated by massive oblique shearing (Fig. 1). It records the very long history of the subduction of the Pacific oceanic plates beneath the advancing North American continental plate.

The Western Cordillera, including the Canadian and American Rockies, was formed largely in Mesozoic times as an orogenic belt above the subduction of the eastern Pacific plates, which were moving east. This orogenic belt was added to the western edge of the very old continental craton known in part as the Laurentian Shield. Then the divergent boundary of the Pacific Rise was overridden by the advancing North American plate. Thereafter, the subducting Pacific plate was moving northwards – introducing an element of shear along the essentially convergent boundary. A later modification was the change of the Pacific plate movement towards the northwest, about 42 million years ago; this occurred when some intra-Pacific boundaries died out, and is best indicated by the bend in the Hawaii–Emperor seamount chain over the famous hot-spot.

The Pacific plate is now moving northwest, and is being subducted beneath the Aleutian zone along the southern margin of the Alaskan continental slab. West of Valdez, this may therefore be considered as an active orogenic belt. Continental material forms the Alaskan Peninsula and the shallow Bering Shelf north of it; but westwards there is only oceanic plate – so the Aleutian Islands are just an island arc over the convergent boundary. The oblique impact of the Pacific plate, especially east of Valdez, has generated long tear faults, including the active Denali Fault.

Accretion of the Alaskan terranes

The long period of northward movement of the Pacific plate had the effect of a massive conveyor belt carrying various terranes from distant sites northwards to be added onto the south coast of Alaska. The individual terranes have been recognized by detailed mapping and an overview of the metamorphic facies (Dusel-Bacon *et al.*, 1989–94); they are not easily recognized on a brief field visit. Only some of the terrane features are identifiable on the geological map (Fig. 2); the Chugach terrane is the Mesozoic greywacke between Valdez and Anchorage, and the Yukon–Tanana terrane is bounded by the Denali and Tintina faults.

Prior to the Triassic, nothing of modern Alaska was recognizable. Through the Upper Palaeozoic, a huge greywacke sequence accumulated along the west coast of the North American craton – including Wrangellia near the equator. Early Jurassic times saw the arrival of the Yukon–Tanana terrane on the great Pacific conveyor belt; this was a chunk of Precambrian–Palaeozoic schists, drawn out into a long strip of country by the shearing of the oblique collision – as were all the subsequent terranes.

Activity increased in early Cretaceous times. The Wrangellia, Alexander and Taku terranes arrived, along with smaller terranes squeezed into the coastal shear zone south of Juneau. Between their different components,

0016–7878/95 1995 Geologists' Association

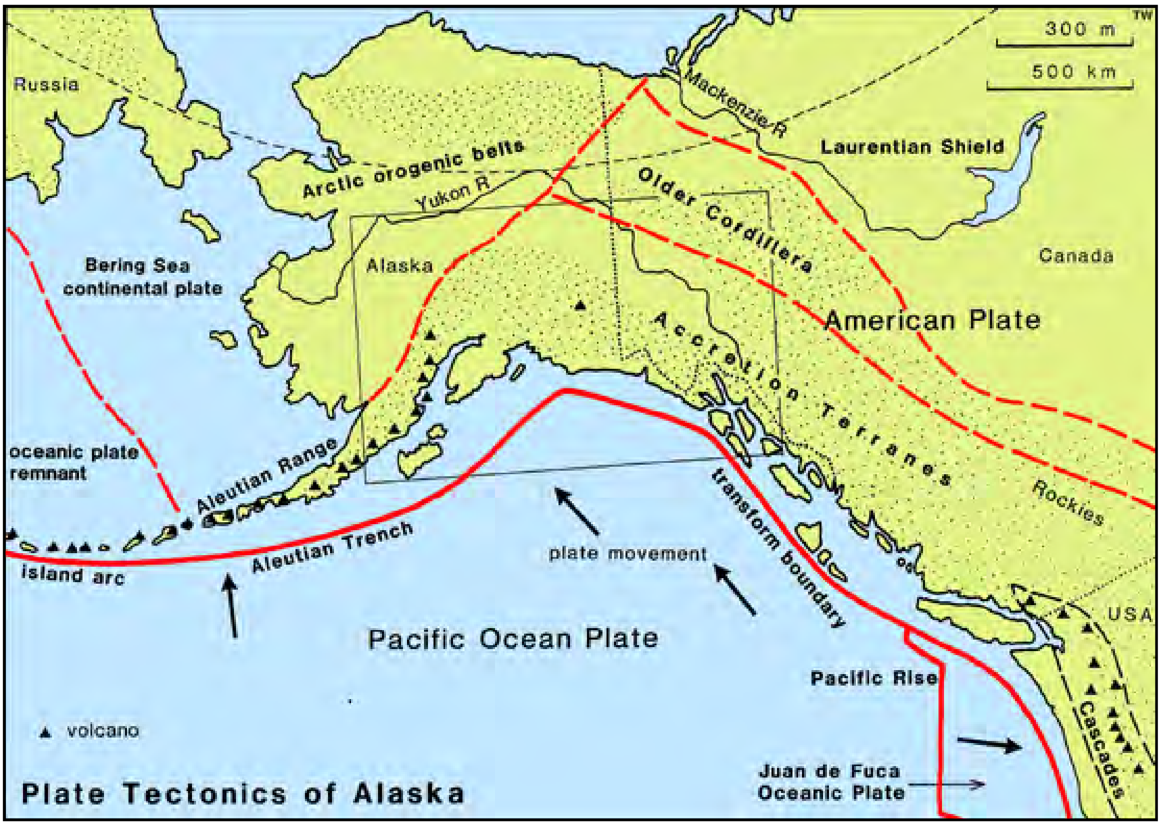

Fig. 1. Outline map of Alaska and its plate tectonic features. The box frames the area shown in Figs 2 & 3.

greywacke belts were trapped and compressed, and the impact of the terranes colliding with the Alaskan continental slab was great enough to create the huge coastal batholith of granite, now exposed around Skagway. The Chugach terrane of Mesozoic turbidites arrived in the late Cretaceous, and two more terranes (of more turbidites) subsequently slipped in rather more obliquely. Continued movement of the Pacific Plate has caused Alaska's largest earthquakes along the sparsely populated coast between Glacier Bay and Prince William Sound.

While southern Alaska was being constructed by terrane accretion, on the Pacific conveyor belt, the Arctic plate was moving and rotating round the northern margin of the American craton. Northern Alaska consists of more orogenic belts and greywacke sequences, with accretion on a lesser scale than the south coast activity. There are also major extension basins which collected thick young sediment piles – including those which house the north coast oilfields.

In Tertiary times, the orogenic belt of the Alaska Range became dominant, and the mountains rose to their present heights. Thick molasse sequences were deposited on both sides of the new range – the continental sediments inland to the north, and 1500 m of marine sediment, containing yet more oil, in Cook Inlet to the south. Volcanic activity and earthquake jolts continue over the current subduction zone sloping north beneath from the floor of the Aleutian Trench.

Geomorphology of Alaska and Yukon

Though Alaska is often regarded as a region of modern glaciers and Pleistocene glaciation, a very large part is dominated by periglacial processes in areas never reached by surface ice (Fig. 3). This was because the coastal mountains catch all the snow, leaving the interior in a deep rain shadow – the Arctic coast is a cold desert. The Yukon is even further from Pacific Ocean moisture, so it too is a periglacial environment (ancient and modern).

Alaska's glacial expansions started well back in the Tertiary, as world climates cooled from the Cretaceous optimum. The glaciation most influential on modern landforms was the Wisconsinan, equivalent to the Devensian in Britain. As in Britain, the earlier glaciation during the Illinoian was slightly more extensive. The Cordilleran ice sheet developed by the coalescence of all the glaciers and ice caps on the coastal mountain ranges, including the Alaskan Range. Most of interior Alaska and Yukon was not glaciated, due to the lack of snowfall. This ice-free belt extended west to the Bering land bridge to Asia, revealed when sea-levels fell to balance ice sheet expansion; this

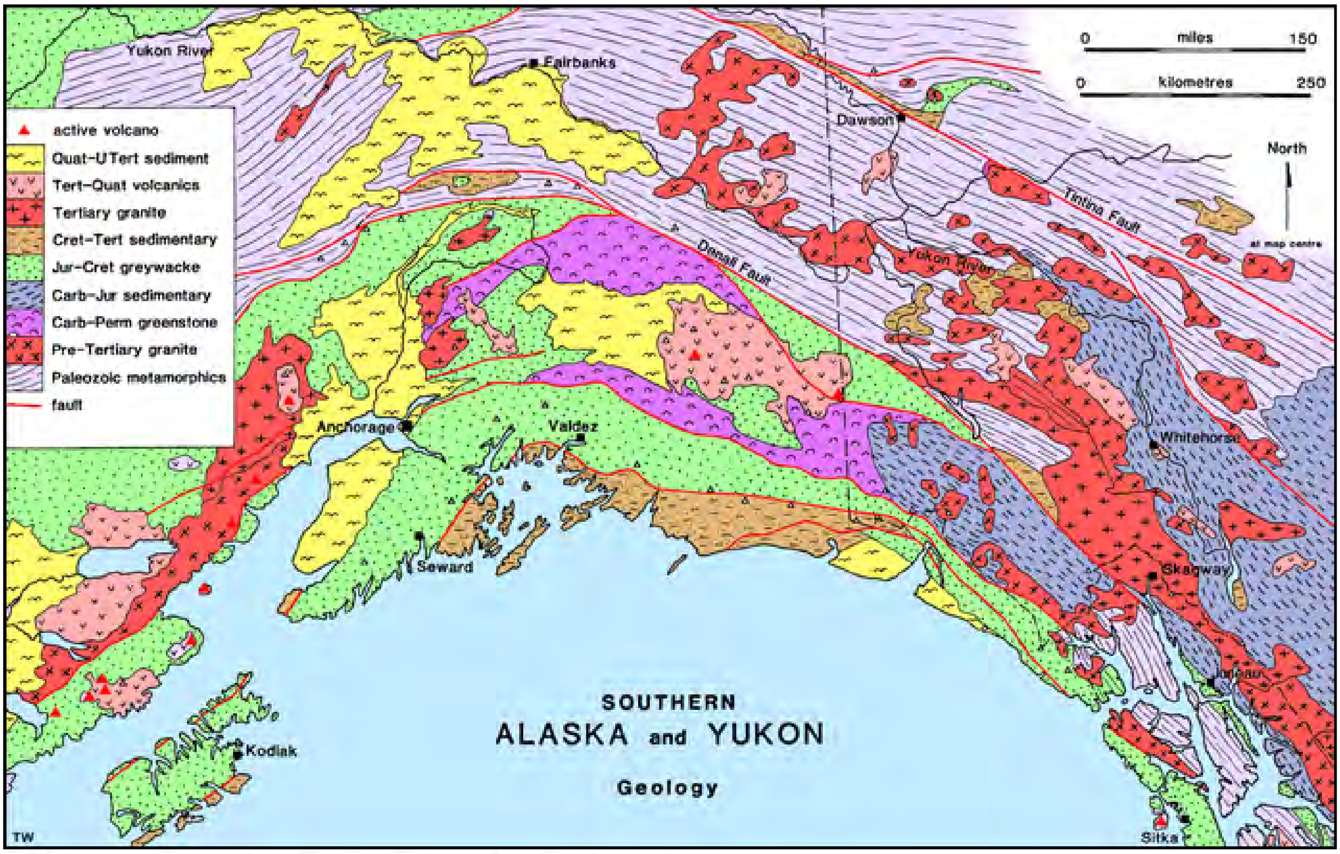

Fig. 2. Simplified geological map of southern Alaska and Yukon.

land connection created an important migration route for both humans and animals during the late Devensian.

The late Neoglacial Little Ice Age started about AD 1400, and reached a maximum around AD 1750. Nearly all Alaskan glaciers are now in retreat, at rates of 3–150 m per year, with temporary exceptions in those which exhibit occasional surges.

The periglacial zones are distinguished by the high plateaus and minimal relief of altiplanation; river valleys are minor, hollows are filled and aggraded by solifluction; the very reduced erosion rate was of critical significance to the preservation of the Klondike gold deposits in the Yukon interior. Continuous permafrost occurs where the mean annual air temperature is lower than about −8°C; this covers the Arctic coast zone of Alaska and Yukon, and also some of the higher mountain areas. There is discontinuous permafrost where mean air temperatures are −1° to −8°C, and this covers most of the Alaskan and Yukon interiors. The permafrost depth is determined by both the surface cooling and geothermal heat melting it from below. Around Dawson it is 20 m deep, but it reaches 100 m deep at the Arctic Circle. Beneath the permafrost, the unfrozen talik is an important groundwater resource; above it, the active layer becomes an undrained, unstable quagmire just a few metres deep during each short Arctic summer.

2. THE 1994 EXCURSION

The concept of a geological tour to Alaska and the adjoining parts of the Canadian Yukon grew after the leader visited part of the region in 1990; the event matured into a joint venture under the wings of the Geologists' Association, Birkbeck College and Trent University.

On August 22, the group of 40 members flew from London to Seattle. They then travelled overland to Vancouver, by train and bus through the Canadian Rockies, and by coastal ferry up the Inland Passage to Juneau. From there the route (Fig. 3) traced the features described in the following pages, by plane and boat to Glacier Bay and Skagway, then by bus through the Canadian Yukon to the Klondike, over into Alaska and through the mountains to Valdez for the ferry towards Anchorage, where the group had to split into two halves. Each half visited Katmai, and also went to either Denali or Kenai. Reunited, everyone flew back to Seattle for a brief visit to Mt St Helens before returning to London on September 12.

The excursion was voted a spectacular success – which had been aided by stunningly good weather. The timing had been designed to avoid the crowds of August and the voracious mosquitoes of July, and also to catch the colours of the brief autumn in September. Rain is always a risk in coastal Alaska, but the group enjoyed an exceptional

Fig. 3. The main features of the modern and Pleistocene glaciations in southern Alaska and Yukon, and the excursion route described.

number of bright sunny days; only one site was lost to rain, and the Denali half caught the first snow shower of winter. The clear blue skies over the Juneau Icefield provided a highlight of the excursion when seven planes were chartered to take the entire group from Juneau to Skagway. This was an unexpected bonus, but every other site also lived up to expectations.

3. THE ITINERARY

The following notes have been condensed and amended from the guidebook which was prepared for members of the 1994 excursion (Waltham, 1994). This itinerary starts at Juneau and finishes at Anchorage (Fig. 3); it could be followed in about 15 days, but an Alaskan visit really warrants three weeks. Hotels are available at all the breaks in this itinerary, but travel arrangements demand some careful advance planning. Road mileages referred to are those on roadside markers.

Juneau

The Alaska state capital of Juneau, and the Mendenhall glacier, lie on a mix of Mesozoic greenstones and slates, some of which are exposed in the downtown area. Early Tertiary granite underlies the upper Icefield. Juneau was founded when gold was discovered in 1880. Placer mineral was first worked along Gold Creek, which flows through the back of town. Hard rock mining then exploited the host quartz veins within the greenstone, with the early mine 5 km up the creek. Mining ended in 1944, but restarted in 1994.

The Mendenhall Glacier is a major outlet from the Juneau Icefield – which is fed by up to 30 m of annual snowfall. The glacier is now 20 km long, 2.5 km wide and 30 m high at its terminus. It moves at about 1 m per day, but its snout is receding about 10 m per year. A conspicuous terminal moraine, left since the AD 1750 advance, now encloses a small proglacial lake. The visitor centre stands on this, and its site was uncovered by the glacier only in 1940.

Two excellent walking trails flank the glacier. The East Glacier Trail is a 5 km loop, climbing gently from the visitor centre, through beautiful moss forest, with a few closer views down to the glacier terminus. The West Glacier Trail is 6 km each way, climbing steeply from the moraine on the west side of the lake onto a high rock shoulder, giving splendid views down to the glacier; a second shoulder about 300 m above lake level provides a fine

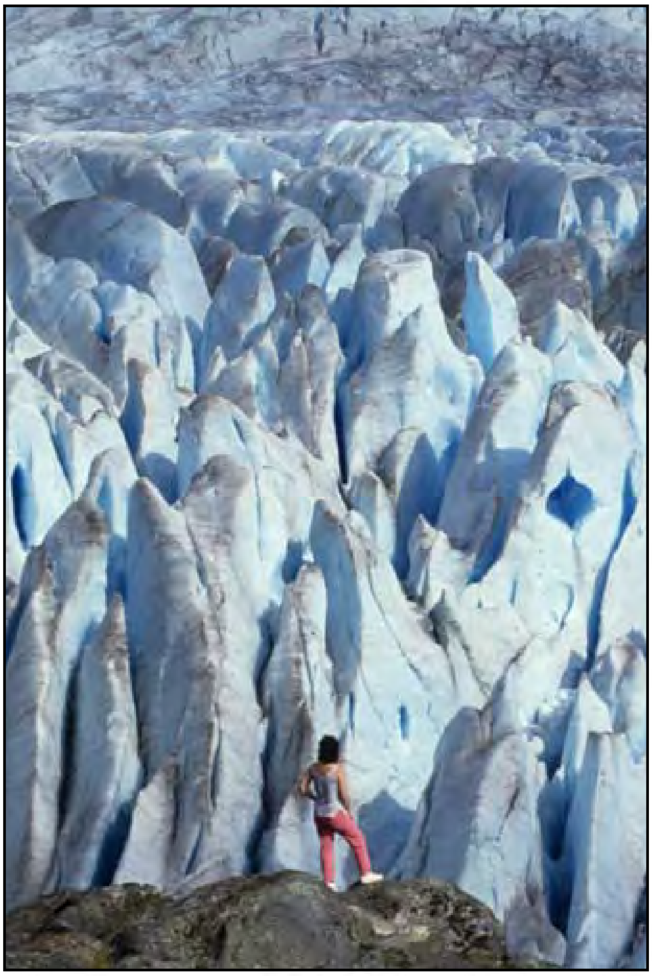

Fig. 4. Seracs and crevasses on the Mendenhall Glacier, seen from the West Glacier Trail. (All photos by the author.)

overlook onto a major serac field with deep crevasses in blue ice (Fig. 4), and can allow a judicious approch to the glacier margin, seracs permitting.

Glacier Bay

When George Vancouver explored an ice-choked Icy Strait in 1794, Glacier Bay barely existed – it was occupied by a massive valley glacier with many tributaries. When John Muir came by in 1879, the ice had retreated 75 km up the bay. Today, the front of the main Grand Pacific Glacier is another 20 km further from the open sea (Fig. 5).

This enormous glacial retreat is unequalled anywhere else in the world, though its timing does match the worldwide glacier recessions since about 1750. The result is that Glacier Bay is a fine example of a recently deglaciated landscape, displaying a magnificent suite of erosional features on land and along the coastal fiords. Glacier Bay also provides ready access to its collection of 16 tidewater glaciers together with many more glaciers which terminate above sea-level (Powell, 1984). Today the different glaciers are in various states of advance or recession. Grand Pacific is slowly advancing and has recrossed the border from Canada, but is heavily choked with sediment. Johns Hopkins, fed from the highest peaks of the Fairweather Range (up to 4670 m), is advancing steadily, Margerie is stationary, Tyeen surges periodically, and Muir is in slow retreat.

The rocks of Glacier Bay are mainly Silurian clastic sediments and limestones, all slightly metamorphosed and strongly folded and faulted. They have been intruded by Cretaceous and Tertiary granite and granodiorite (and gabbro in the Fairweather Range), which are associated with extensive mineralization bearing gold, copper, zinc, nickel and molybdenum. Some gold has been worked on a small scale in the past, and other orebodies could be economic except for the remote location and protected status within the National Park. Glacial till forms moraines at various locations, and the flat land around Gustavus lies on very recent outwash gravels and sands.

Glacier Bay is best reached on a mini-package tour including the flight from Juneau to Gustavus, the connecting bus and a day-long cruise. The boat cruises slowly up the fiord, often very close to the rocky shores to enable viewing of the wildlife and geology. Around Bartlett Cove and on the low gravel Beardslee Islands, the spruce–

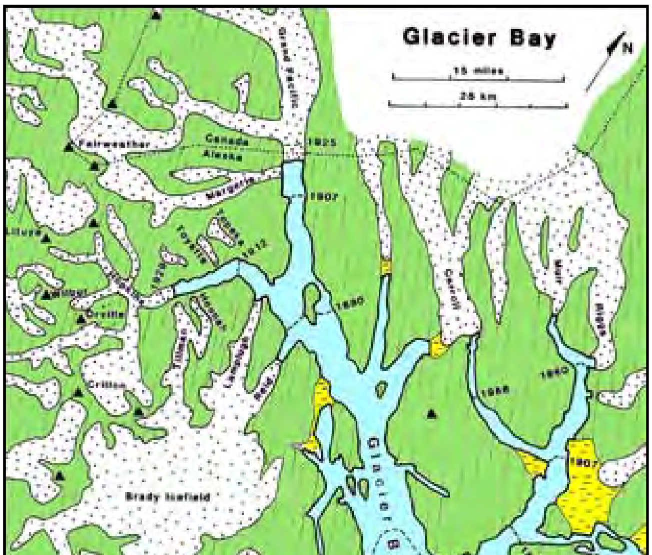

Fig. 5. The main icefields and glaciers of Glacier Bay, and positions of the ice fronts mapped in the past.

hemlock–moss rain forest is only 200 years old, and the vegetation becomes progressively younger with distance up the bay. An added attraction on the tour is the wildlife, notably puffins, seals and sea-lions, bald eagles, and the occasional brown bear, orca and humpback whale.

The Marble Islands are ice-scraped knolls of metamorphosed Silurian limestone; their shore crags display spectacular large-scale glacial striae and grooves, with some plucking at joints. There are numerous views of glaciers on each side of the bay, with caves at their snouts, meltwater streams and moraines on the ice, and also splendid U-shaped valleys. On the left, Reid Glacier and Lamplugh Glacier are the first to descend all the way to tidewater; the boat approaches close to both; Lamplugh is notable for the deep blue of its seracs. The cruise then continues up either Johns Hopkins Inlet or Tarr Inlet, depending on which of the glaciers are currently in a more spectacular state; in either inlet the boat stops in front of the glacier for long enough to see calving when ice blocks collapse into the sea.

Just into Johns Hopkins Inlet, the south wall exposes a fine contact of granite intruded into Cretaceous phyllites; granite veining and phyllite xenoliths are clearly seen. On the north side, Toyatte Glacier is scarred by a pile of landslip debris moving down as an oversized patch of medial moraine. Johns Hopkins Glacier, at the head of the fiord, terminates in a wall of ice over 30 m high; it is banded with dipping layers of till through its northern half, but the southern side is clean blue ice.

Tarr Inlet is cut wholly in Cretaceous granites. At the head of the fiord, the Margerie Glacier is white and clean, as it is short and steep with a low sediment load and little melting in its rapid descent through the melt zone; its face is 60 m high, with another 120 m below the water which is 250 m deep. The adjacent Grand Pacific Glacier is low, wide and black with sediment, as it has travelled far through both erosional and melt zones.

Juneau to Whitehorse

The normal route north to Skagway is by ferry up the Lynn Canal, but a short plane ride offers an alternative. The Lynn Canal fiord lies along a major fault separating older phyllites and greenstones on the west from younger gneisses and granites on the east. If the weather is clear, the flight offers stunning views of the glaciers of the Juneau Icefield, laced between the granite mountains of the Coastal Batholith.

The town of Skagway grew from a single cabin when the Gold Rush stampeders arrived by boat from Seattle in 1897. Northwards, the road climbs steeply over the Tertiary batholith which extends south beneath the Juneau Icefield. Various roadcuts offer splendid exposures of granite with xenoliths, migmatite, amphibolite and dolerite dykes. Beyond the White Pass summit, and into Canada, the road crosses a splendid knock-and-lochan landscape etched into ice-smoothed granite outcrops. Alongside Tagish Lake, Eocene volcanics are stained red due to hydrothermal mineralization with veins worked for gold and silver by the Venus Mine, of which the remains of the mill lie below the road. The Carcross Desert is an area of sand dunes beside the road, where wind-blown sand has been derived from glacial outwash and dried lake sediments.

Just before Whitehorse, the Yukon River flows through Miles Canyon. A shallow gorge exposes late Pliocene basalts with large columns defined by polygonal cooling joints, beneath a cover of glaciofluvial sediment.

Whitehorse is the capital and only large town of the Yukon, built on the left bank of the Yukon River. Overlooking the western edge of town, a terrace is made of Pleistocene silt deposited in a large pro-glacial lake which occupied the Whitehorse Trough within the Yukon valley. The Yukon originally flowed southwest to reach the ocean just north of Glacier Bay (Fig. 3); Miocene uplift of the coastal mountains caused the river to cut a deep trench through, but Pleistocene ice on the new mountains blocked this outlet, and ponded the lake which overflowed northwards to establish the modern river course (Templeman-Kluit, 1980). Clean sections at the top of the bluffs expose a light-coloured band, 30 mm thick; this is the White River airfall ash from a Plinian eruption about 1300 years ago of a volcanic vent on the flank of Mount Bona, in the Wrangell Mountains just west of the Alaskan border. Many small landslides have occurred along the bluffs whenever and wherever the trees have been cut down; stabilization has been achieved by re-vegetation.

Whitehorse to Dawson

The Klondike Highway roughly follows the Yukon valley north to Dawson. At Km 299, a geological roadside exhibit describes fallen blocks of massive Jurassic conglomerate formed on the front edge of a continental mudflow. Across the road are excellent exposures of the White River Ash, which is seen in most of the roadcuts and river cliffs in this region. The Five Finger Rapids are formed around four crags left where the Yukon River has entrenched through a low escarpment of similar Jurassic conglomerates. An extensive alluvial terrace stands 30 m above the river.

West of Moose Creek there is an overlook across the Tintina Trench. This is a major graben trough cutting across most of the Yukon; it is bounded by normal faults 5–20 km apart. On both sides are outcrops of Palaeozoic metamorphics (including the Klondike Schist on the south), but parts of the trench are floored with Cretaceous and Tertiary sandstones, shales and lignites. As a topographic feature, the trench is not always clear, but it holds straight sections of the Pelly, Stewart, Klondike and Yukon rivers.

Just short of Dawson, the Dempster Highway leaves to the north. After 80 km it crosses the North Fork Pass, through the Ogilvie Mountains. This makes a worthwhile side excursion to view the tundra landscape and periglacial features. A walk up the hillside east of the pass summit reveals lobate solifluction flows and distant views to the syenite spire of Tombstone Mountain. Hillside and roadside exposures reveal black quartzites and metamorphosed Precambrian lavas and agglomerates.

North of the pass, the Dempster continues as another 690 km of dirt road across a spectacular and empty wilderness to Inuvik on the Mackenzie Delta. From there, Tuktoyaktuk is only reached by plane in summer. Built on and surrounded by pingoes, this Inuit village on the Arctic coast attracts geologists to its unforgettable periglacial environment (French & Heginbottom, 1983); the highlight is a visit to the village cold store, which is a series of tunnels and rooms cut in the layered ground ice of a pingo. Tuktoyaktuk involves an extra four days out of Dawson (and was not included in the 1994 tour).

Dawson City

The town grew from nothing in 1896 when prospectors from the older town of Fortymile moved here in the wake of the Klondike gold discoveries. Some 30 000 stampeders arrived in 1898, and within two years a stable township had evolved from the original tent city. Timber buildings and raised sidewalks lined the muddy streets – which have never been tarred. There was a railway to the head of Bonanza Creek from 1906 to 1914, and the Yukon government was here until 1953. Now Dawson has a population of about 700, with more in the short summer to service the visitor influx. Winter temperatures fall to –60°C.

With a mean annual temperature of –5°C, Dawson lies in the zone of discontinuous permafrost (French & Heginbottom, 1983). Ground ice reaches depths of 20 m; the top 1–2 m form the active layer. Only an outer strip, warmed by the river water, has no permafrost. Most of the town stands on frozen silt, with thaw-stable gravel only at depths greater than 4 m.

The older houses, built largely in 1898–1903, stood directly on the ground. Internal heat therefore melted the ground ice that supported them; most subsided, many were jacked up and levelled, others were demolished. Some subsided buildings, on the least stable ground close to the edge of the permafrost area, have been preserved – and perfectly demonstrate permafrost subsidence.

Correct building practice on permafrost entails preserving the ground ice by ensuring that there is sufficient insulation between any building heat and the ground beneath. Buildings stand perfectly well on stable ice. The simplest insulation is provided by a clear air space; consequently all new Dawson buildings stand on wooden blocks keeping them clear of the ground; these can be seen on any walk around town. Water pipelines and electric cables are buried and well insulated within the active layer.

The conspicuous Moosehide Slide in the slope of Klondike Schist above the north end of Dawson may have occurred in part because the slope debris was saturated where internal drainage was prevented by the impermeable permafrost. The slide is not old as it is recorded in Indian legend, but it now appears to be stable.

The Klondike Gold Rush

Gold had been found at Fortymile, down river from Dawson, in 1887, and by 1895 there were hundreds of prospectors and miners on most of the creeks draining into the Yukon River. Robert Henderson first panned a little gold in Rabbit Creek (now known as Bonanza Creek), and on his advice George Carmack and two Indian friends camped on Rabbit Creek 15 km up from the Yukon. On August 16, 1896, they found gold richer than their dreams in the creek gravel. They staked their claims, and went to Fortymile to record them.

Within days, hordes of other miners from up and down the river followed the stories; by the end of 1896 most of the Klondike creeks had been staked as claims (Fig. 6). The next year, 1897, the river terraces high above the creek beds had been prospected, had been found to be rich in gold, and had also been staked. Claims cost just $15 to register, and more than 30 claims on Bonanza and Eldorado creeks each yielded a million dollars in gold.

On July 17, 1897, a ship docked in Seattle carrying 68 miners and $700 000 in gold, and the world's most frantic gold rush began. Every ship on the west coast sailed north, and by the end of autumn 30 000 stampeders were camped at Skagway and Dyea (at the fiord head 2 km west of Skagway). The White Pass from Skagway, had a pack-horse trail with tolls which few stampeders could afford. Throughout the winter of 1897–98, some 25 000 stampeders hauled their supplies through deep snow and horrendous cold, over the 990 m high Chilkoot Pass, north from Dyea. Once at Lake Bennett, the stampeders camped again, cut down much of the surrounding forest, made a motley collection of boats, and awaited the spring thaw. When the ice broke up in May, 7124 boats floated down the river. This soon joined the Yukon River where the current carried them downstream, and through the rapids of Miles Canyon and Five Fingers, for 900 km to Dawson. The armada floated into town in June 1898, by which time all the ground along the creeks and the terraces was already staked; the new arrivals, who had toiled over the Chilkoot in winter, could only work for wages on others' claims or leave in despair.

Origins of the gold

The Klondike gold occurs largely as placer deposits along most of the creeks in an area of over 1000 km^2. The richest gravels, just a few metres thick, are mostly covered by up to 12 m of barren gravel, loessic silt and peaty organic muck. Late Tertiary gravels, 2–50 m thick, occur as terraces and over the hills between the creeks, at levels up to 100 m above the creeks; these also contain gold, the richest in the White Channel, named after its clean, white, quartz sand.

It had long been assumed that all the gold, in the White Channel and in the modern gravels, was typical alluvial placer material, derived by mechanical erosion of bedrock gold-bearing quartz veins and then concentrated by selective deposition. But this is not entirely the case. The marine clays which now form the Klondike Schist originally contained low levels of gold. This was mobilized during Cretaceous metamorphism, at temperatures around

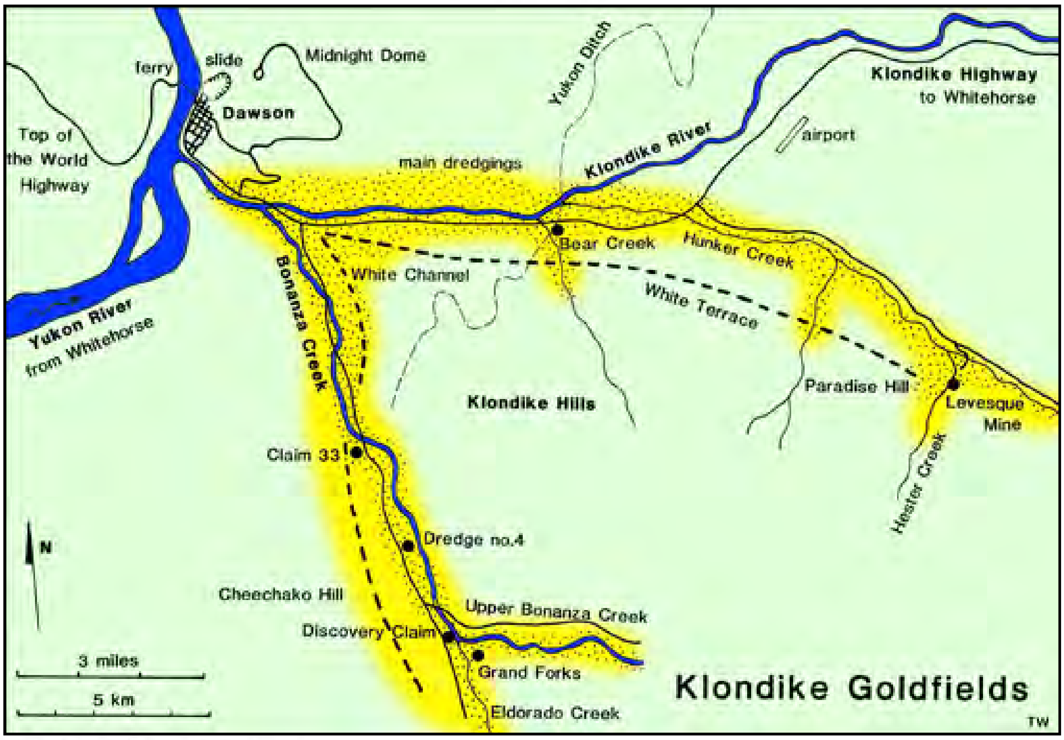

Fig. 6. Sketch map of the Klondike goldfields.

300°C, into numerous dispersed quartz veins (Rushton, Nesbitt, Muehlenbachs & Mortensen, 1993).

The braided channel sediments of the White Channel terrace are of Plio-Pleistocene age (Morison & Hein, 1987), and they are also mineralized. Their lower parts show clear signs of low-temperature hydrothermal alteration, notably kaolinization with new growths of clay minerals. Similar alteration occurs in the upper parts of the immediately underlying bedrock – the quartz chlorite sericite schists of the Lower Paleozoic Klondike Schist. This second phase of gold mobilization (largely by rainwater) concentrated the metal to economic levels just above and below rockhead. Gold/silver ratios vary from creek to creek, indicating their localized sources and emplacement processes. This explains the lack of any Mother Lode in the Klondike. Vein mining in the region has never been fruitful.

Erosion and reworking of the mineralized sediment by the contemporary early Pleistocene rivers produced further gold concentrations in the White Channel – as traditional placer deposits. Fortunately, Pleistocene ice did not reach the area; instead, fluvial erosion of some of the sediments produced a second generation of placer deposits in the modern creek gravels (and in the intermediate terraces). In all the placer gravels, the pay streaks with the very richest gold lie immediately above the rockhead and follow the ancient channels cut into the bedrock; the positions of these can never be predicted before excavation down through the entire thickness of the muck and gravel – much to the frustration of many exhausted miners.

Mining the gold

Panning for gold entails washing water across a shallow bowl fast enough to remove the light sediment and leave behind the heavy gold. With this quick and simple technique, the prospector worked his way up the creeks, panning the streambed gravels, until he produced a rich pan. Then he staked his claim, 500 feet (150 m) along the creek and 1000 feet (300 m) up each side, and had to start digging into the deeper gravels, largely frozen solid in the permafrost, as the richest gold was always down on the rockhead.

Hand mining was the technique of the frantic Gold Rush years, but it only lasted until 1904. A shaft was dug straight down until bedrock was reached, and then horizontal adits were dug to follow the pay streaks. All this involved melting the permafrost, by fire-setting or with steam or water. In winter, gravel was dug out and stockpiled on the surface, where it froze solid. Then in summer, the stockpiles were sluiced in running water, while the unfrozen and unstable shaft was temporarily avoided.

Sluicing is the method of separating the gold from the quartz and rock gravel. Screens (sieves) are used to remove all the gravel coarser than about 10 mm. Then the fines are run into the sloping sluice, where they are washed over the riffle bars on its base; the old sluices were long wooden troughs, but the modern ones are shorter and in steel. The gold is trapped behind the riffles, too heavy to be washed over by the water flow; the finest gold dust is trapped on cloth (or nylon matting today) beneath the riffle bars. The sediment from behind the riffles is panned to yield its gold.

Hydraulicking was started in 1902 and is still the favoured method on the terraces. Powerful water jets wash the gravel from an exposed slope (Fig. 7); it is then scooped up and dumped into sluices just as in hand mining. It is quicker than digging, but requires a good water supply; long aqueducts were built in the early years.

Dredging was the great gold producer in the years 1905–66, when up to 35 dredges operated on the creeks. A floating dredge could weigh 3000 tons, and sat in a lake of its own making. At its front, a chain of 75 buckets, each holding $0.5\ m^3$, could scoop up $8000\ m^3$ of gravel per day. Inside, revolving drum screens and normal sluices, took out the gold, and dredging had to stop when these froze every winter. At the back, a conveyor dumped the waste – where the swinging motion needed for the bucket chain resulted in the distinctive crescentic banks. A dredge just ploughed through the valley gravels, leaving its sinuous ridge of tailings. It could reach to a depth of 17 m, and normally scraped up the top 3 m of the altered schist to ensure no gold was missed. One dredge could gather up to 800 ounces (11 kg) of gold in a day; this was a yield of about one part per million, though the hand miners achieved far higher values by picking off the rich pay streaks.

Cat mining began in 1973 and uses a caterpillar bulldozer to clear away the muck and barren gravel, before piling up the gold-bearing gravel ready for sluicing. It is crude and simple, but is still used where there is not enough water for hydraulicking.

Gold production from the Klondike has totalled over 300 tonnes. Annual yields have fluctuated with changes in mining methods and also with the price of gold, but are maintained today with many small hydraulicking and cat mining operations.

Round the goldfields

The valleys of the Klondike River, Bonanza Creek and Hunker Creek are almost entirely floored by snaking ridges of dredged tailings, and the small mining operations still active are mostly tucked away in the side creeks (Fig. 6). Hester Creek supports two small mines which were visited on the 1994 tour.

The Fritz Mine is a one-person cat operation on a newly staked claim out in the wilderness. A bulldozer is used for about 6 months of the year to move 8 m of muck and barren gravel to expose bedrock; a sluice is in place, but the pay streak has proved elusive.

The Levesque Mine is a two-person hydraulicking operation on a productive claim leased from its owner for a royalty. Overburden of 5–20 m of muck and gravel is washed away, revealing numerous very large bones and tusks from Pleistocene mammoths. The lower gravels have good gold values; the richest gold does not occur in the bedrock troughs where placers should be – instead it is over bedrock ridges and associated with graphite mineralization, reflecting its primary hydrothermal origins. Monitor pumps blast out 5000 l of water per minute, and rapidly cut through the unfrozen sediments and the upper zone of mineralised and weathered schist. The ground is thawed because earlier miners dumped their tailings and killed the insulating blanket of moss. In winter, the muck freezes to 2 m deep beneath a snow cover; the exposed face would freeze back inwards for 5 m, delaying the spring start-up; so the monitor is used to undercut and slump the face before winter – leaving a low profile which holds an insulating cover of snow and therefore freezes less deeply.

Fig. 7. Hydraulicking at the Levesque Mine in the Klondike goldfield. The water jets are washing out the full thickness of muck and auriferous gravel, and also the top few metres of the altered gold-bearing schist – exposed above the excavator.

Up Bonanza Creek, signboards on numerous roadside turnouts tell of the mining history. The last large dredge is an excellent preserved feature, and a commercial site on Claim 33 offers visitors the chance to try panning for gold dust – though one member of the 1994 group found her own nugget.

A road climbs to the summit of Midnight Dome, a broad tor of serpentinized ultrabasics left above the schist plateau level. It offers splendid views over the Klondike valleys with their sinuous ridges of dredge tailings, the old White Channel terrace workings, and Dawson and the Yukon valley. Road cuttings expose crumpled chlorite schist.

Dawson to Delta

A free ferry crosses the Yukon River from Dawson to the start of the Top of the World Highway, which crosses the tundra to the USA border. The road is built largely along the interfluves at plateau level, giving fine views of the periglacial landforms. A product of cryoplanation, the plateau is broken by isolated tors, such as Castle Rock formed in Palaeozoic quartzite, and entrenched by fluvial valleys. Solifluction lobes and stone stripes can be found on various slopes, notably near the frontier.

Into the USA, the remains of the Jack Wade dredge lie in a roadside creek; 20 km beyond, a long roadcut exposes a porphyry dyke, with amphiboles and zoned feldspars, intruded into greenstone with baked margins.

Beautiful downtown Chicken, just off the highway makes a memorable coffee or lunch stop; it is the centre of a dispersed and slightly peculiar community of hunters and gold miners. Cuttings along the road beyond Chicken reveal granite with dolerite dykes (at Mile 57) and syenite with perthitic feldspar phenocrysts (at Mile 33).

The Alaska Highway is joined just before Tok. The road was built by the military in 1942 as a desperate measure in case of possible Japanese attack of Alaska. It is 2275 km long, linking Dawson Creek, on the Canadian road system in British Columbia, with Delta, on the older Anchorage–Fairbanks road. The rapid construction occupied 11 000 troops. Their inexperience of dealing with muskeg (peat bog) and permafrost, which they destroyed by stripping off the organic cover, caused them to spend a lot of time sunk into quagmires of mud. Most of the Highway now stands on a thick gravel pad, to ensure stability by preserving the permafrost, and one embankment just east of Tok has internal air ducts which transmit cold winter air; some parts of the road are still wavy due to settlement on the muskeg. The route to Delta is through continuous forest of hemlock, spruce, birch and aspen; it crosses three rivers, and the bridge over the Gerstle gives the best view of braided channels in the outwash and the Alaska Range mountains to the south.

The Trans-Alaska Oil Pipeline

This infamous pipeline carries raw petroleum (crude oil) from the Prudhoe Bay oilfields on the Arctic north coast to Valdez, the ice-free port on the Pacific south coast. It was built in 1975–7, and is 1277 km long, with 12 pumping stations and a tank farm at the Valdez terminal where tankers are loaded. The pipe is 1200 mm in diameter and made of 12 mm steel; it carries 1.5×10^6 barrels (250 000 t) of oil per day at a steady speed of about 10 km h^{-1}. The petroleum flows out of the ground at about 75°C, and is kept at 40–60°C through the pipeline, at which temperatures it flows most easily. The whole pipeline is therefore insulated with 100 mm of polyurethane foam and fibreglass inside the aluminium cladding.

Most of the route is across discontinuous permafrost, and this has to be preserved to ensure stability, as any subsidence could cause a fracture and massive environmental damage. Three alternative modes of construction have been used:

(1) Conventional burial for 655 km: in trenches 3–12 m deep where there is no permafrost or minimal ground ice, or in thaw-stable rock or gravel.
(2) Above ground on piled trestles for 611 km: hollow steel piles reach 5–20 m down into stable ground or permafrost beneath the active layer. Most piles are into the permafrost, and therefore each one has its own internal, self-operating refrigeration system so that they remain frozen into the ground ice; internal tubes carry ammonia, which rises as a warmed gas into the heat fins on top, and in winter sinks as a cooled liquid back into the buried section of pile. The pipeline is flexible and is designed in zigzags; it rests on cradles which can slide on the cross-beam supports to accommodate thermal contraction in the winter.
(3) Frozen burial for 11 km: these are short sections beneath roads and caribou migration routes; the ground is kept frozen either by buried pumped refrigeration pipes, or by the automatic thermal piles.

Delta to Valdez

The Richardson Highway south from Delta follows the oil pipeline through the Alaska Range and Chugach Mountains on its route to Valdez. Out of Delta at Mile 266, the road climbs gently up the outwash fans from Pleistocene glaciers, and then up onto the terminal moraines (Pewe & Reger, 1983); at Mile 248, a Holocene fault scarp forms a step 3 m high. Inside the moraines, knob-and-kettle topography has lumps and hollows on glacial till, on a smaller scale than ice-scoured knock-and-lochan terrane on bedrock.

The first pipeline viewpoint, with a geological display, has a good view north of the pipeline on refrigerated piled trestles; under the road the pipeline is in a polystyrene-lined trench cooled by thermal piles; the Alaska Range overlooks the site.

Black Rapids Glacier lies west of the road, with lumpy moraines in front and a conspicuous vegetation trim-line, probably from the 1750 glacial maximum. The glacier achieved fame in 1937 when it surged with an advance of up to 60 m per day. It threatened the road and also the roadhouse (now badly subsided), where a radio announcer was stationed to broadcast details of the ice crunching through the building. But the glacier's surge stopped short of the road, and it has since retreated. At Mile 223, stone groynes in the river channel reduce scour over the pipeline buried in the alluvium; no thermal piles are needed in the thawed ground beneath the riverbed.

At Mile 216, a turnout on the right has a geological display where the pipeline crosses the Denali Fault. This major fault separates the Wrangellia from the Yukon–Tanana and McKinley terranes. It has displaced Cretaceous rocks by 400–700 km, and late Devensian alluvial fans by 5–50 m; it is still active. It is not a plate boundary, as it lies well inside the mountain chain accretion zone on the edge of the American plate; but movement of the Pacific plate is dragging the ground south of the Denali Fault towards the west. There is little vertical displacement; it is therefore a right-lateral strike-slip fault. Across and each side of the mapped fault zone 150 m wide, the pipeline rests in cradles on concrete beams set on an insulating gravel pad (Fig. 8). These are to accommodate up to 7 m of horizontal displacement (and 1.5 m of vertical movement) on the fault. When the earth moves and takes the concrete beams with it, the pipeline cradles should merely slide on the teflon coating of the beams, and distribute the movement into the mildly flexible pipe.

Fig. 8. The Trans-Alaska Oil Pipeline resting on concrete beams which can allow lateral ground movement where it crosses the active Denali Fault.

Fig. 9. Stone polygons created by ice heave in the sediment of a kettle hole beside the Denali Highway.

Rainbow Mountain, at Mile 209, is composed of Carboniferous greywackes, limestones and pyroclastics; it is draped in screes which feed some superb rock glaciers. Gulkana Glacier, with its fine medial moraines, is a little to the south, and Summit Lake lies in a depression left by very late Devensian dead ice within the moraine – it is a giant kettle hole.

At Paxson, the Denali Highway turns off to the west, offering an alternative route to Denali and then down to Anchorage. It is only a dirt road, but it crosses beautiful tundra along the southern slopes of the Alaska Range. Around Tangle Lakes there are many large kettle holes, some of which are now dry with truly spectacular stone polygons formed by ice heave in their sediments (Fig. 9). The road crosses moraines and outwash, passes below rock glaciers, and lies along the crest of a winding esker for over a kilometre; this route does have considerable appeal for the cold zone geomorphologist (Pewe & Reger, 1983).

Further south on the Richardson Highway, a scenic turnout on the left just after Glenallen gives an excellent view across the forested Copper River Basin. The viewpoint is on a terrace of the Pleistocene silts deposited in the Devensian Lake Atna which was dammed near Chitina (80 km to the southeast) by glacial advances from the Wrangell Mountains. Across the basin stand Mt Drum on the left, and Mt Wrangell, 4301 m high, further away on the right; both are Tertiary and Pleistocene shield volcanoes; Wrangell is still active with summit fumarole activity temporarily increasing after local earthquakes, including that of 1964. Smaller bare hills protruding 30–100 m from the forested basin floor are mud volcanoes; warm, mineralized, gas-rich water rises through the sediment carrying fines to the surface where they are slowly re-deposited on cones around the gently bubbling springs; close to, they are not very exciting. About 200 m to the north, the old road is breached by a large active landslide, caused by the Copper River undercutting a high silt bluff on the outside of a bend; this was a predictably bad location for the road, since rebuilt further from the bluff.

The bridge over the Tazlina River is beside another high bluff in sediments of Lake Atna; lithologies vary through the sequence, and the horizons of coarser debris originated as volcanic mudflows. The road climbs southwards into the Chugach Mountains with ever-changing views of glaciated skylines. A pipeline pumping station is passed, with a residential block safely elevated on piles over permafrost. Landslides on the valley side are due to loss of ice support on deglaciation.

The Worthington Glacier is spectacular and accessible from its adjacent car-park (Fig. 10). Its steep ice descends to a proglacial lake 300 m long, dammed by an arcuate terminal moraine from which the glacier has retreated since 1898. Short trails climb the lateral moraine to fine views of the crevassed ice, and exposures of Mesozoic quartzitic phyllite of the Chugach terrane.

Immediately over the Thompson Pass on the highway, a short walk west along a rock terrace gives views of the deep glacial trough below, the line of the pipeline trench, glaciers and arêtes, and post-glacial stream gullies. The road descends into the trough, and through Keystone Canyon, a post-glacial notch through a rock bar left beneath a rising Pleistocene glacier. Approaching Valdez, the old town site is off to the left; located on unstable sediment, it suffered badly in the 1964 earthquake; the harbour was lost when the submarine sediment slope failed as a landslide into the depths of the fiord; then a 10 m tsunami carried ships inland and wrecked the town. The new town, built after the earthquake, stands on an outwash fan of coarse stable sediment, behind a greywacke ridge which provides some protection from tsunamis. It is surrounded by dramatic peaks and snowfields, and the oil terminal lies across the fiord.

Fig. 10. Worthington Glacier in the Chugach Mountains.

The Good Friday Earthquake, 1964

With a Richter Magnitude of 8.6, the 1964 earthquake was one of the strongest ever recorded in North America, and was also unusual in that strong ground motion lasted for more than 4 minutes (the 1906 San Francisco earthquake lasted just 40 seconds). Damage and destruction was extensive in the Alaskan coastal towns from Kodiak to Cordova.

The quake was caused by movement on one of the major thrust faults where the Pacific plate oceanic crust is subducting under the Alaskan continental plate. The epicentre was in the fiordlands west of Valdez (Fig. 11); the focus was at a depth of 25 km – hence the high surface damage intensity. A surface break appeared only on the Patton Bay Fault, far to the south on Montague Island; movement of up to 11 m extended along the 35 km of outcrop. Secondary effects of the quake included massive tsunamis (which hit Valdez, Seaward, Homer and Kodiak), the landslides of Anchorage and elsewhere, and many submarine slides and turbidity flows.

A huge area of ground moved up during the quake; Montague Island was uplifted 11 m (Eckel, 1970). Fossil evidence shows that the uplifted area had been moving slowly down for the previous 1000 years. A smaller area to the north moved down in the quake; Harriman Fiord subsided 2.5 m. Much of the coastal area also moved south by up to 15 m. All this may be interpreted as due to elastic

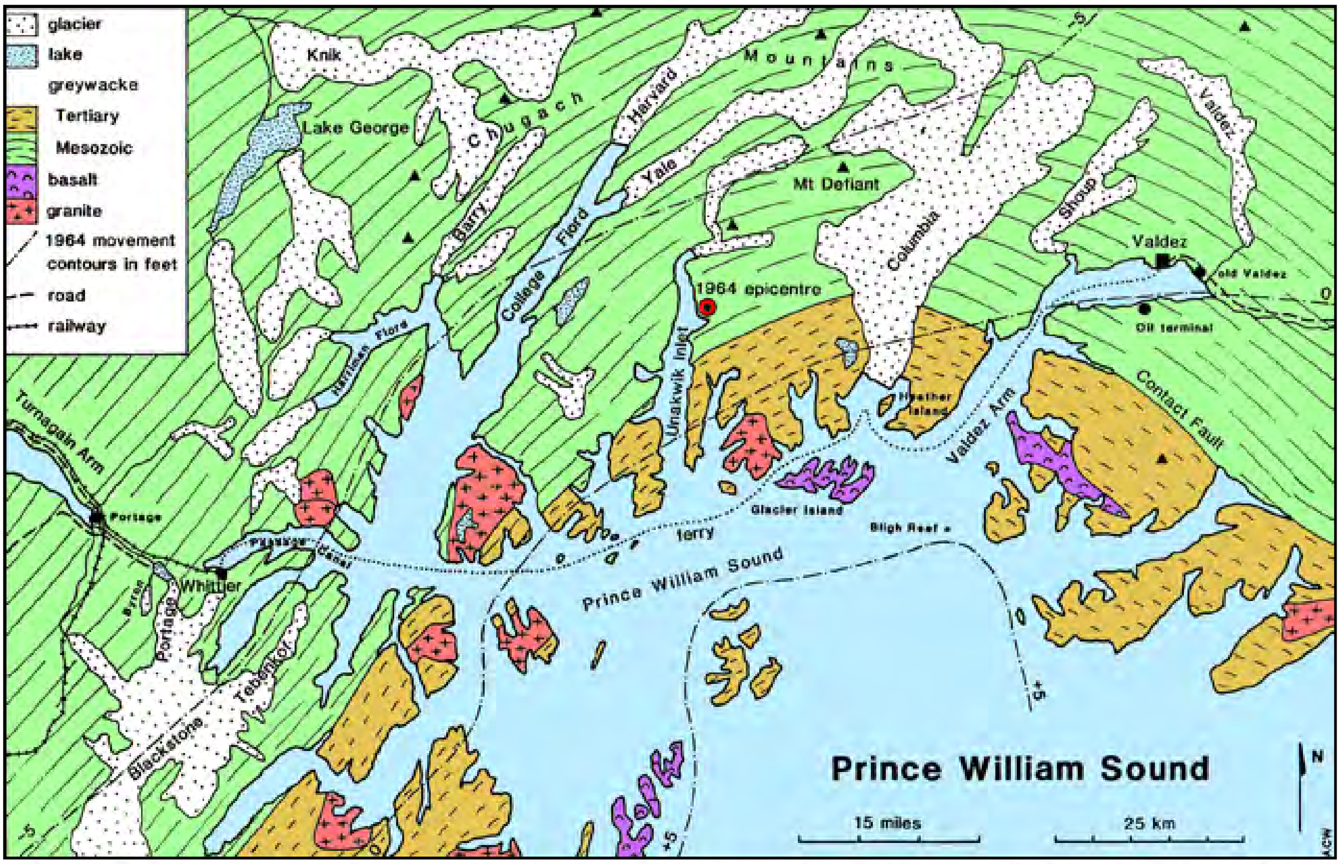

Fig. 11. Outline geology and glaciers around Prince William Sound. Contours depict vertical movement during the 1964 earthquake.

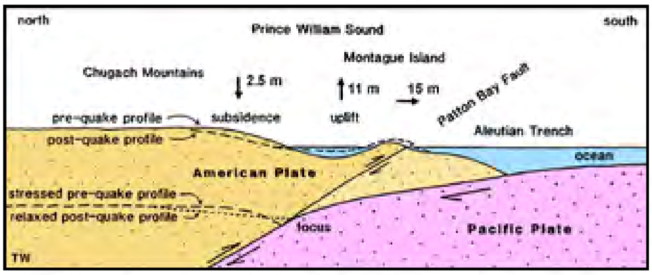

Fig. 12. Schematic diagram of the rock deformation during the 1964 earthquake. The large arrows indicate the maximum components of surface movements.

rebound of the overstressed American plate which had been dragged down by the subducting Pacific plate; when friction on the fault was overcome the American plate front moved up and out, and relaxation allowed subsidence just behind (Fig. 12).

The ferry from Valdez to Whittier

Prince William Sound is crossed by the state ferry, which offers a route towards Anchorage far preferable to the long loop round by road (Fig. 11). The ferry sails out of Valdez Arm fiord, leaving Bligh Reef well to the left. This is the rock hit by the Exxon Valdez in 1989; the tanker had strayed out of its normal lane to avoid small icebergs floating out from the Columbia Glacier. The resultant oil spill plastered much of Prince William Sound. A massive and very expensive clean-up appears to have restored the marine habitats; the sea otters are back, and the Valdez hatcheries now achieve an annual return of over ten million salmon.

Turning into Columbia Bay, iceberg numbers increase greatly, with views up to the Columbia Glacier and Mt Defiant beyond. The glacier flows down at a mean rate of 2 m per day, and ends in ice cliffs 50 m high. It did have a stable front down against Heather Island, but it has retreated from there since 1978, leaving a submerged terminal moraine with its crest 20 m below water level west of the island. Many of the icebergs calved from the glacier become grounded on this moraine. The ferry does not go through this iceberg barrier, but still provides a splendid ice experience.

Returning down Columbia Bay fiord and heading west, the next fiord to the north, Unakwik Inlet, has the 1964 earthquake epicentre near its head. Barry Glacier in the northern distance has good medial moraines, and Tebenkof Glacier closer to the south has a large terminal moraine above sea-level.

Into Passage Canal fiord, the mountain on the north side is an Oligocene granite. The next basin to the west contains Billings Glacier, with a high headwall in horizontal, banded, Cretaceous greywackes; the glacier is unroofing the granite batholith, exposed with a pegmatite dyke below the ice terminus. Dead trees along the north foreshore were drowned by 2 m of subsidence in the 1964 earthquake. The port of Whittier was created in 1942 when the military cut the railway tunnel providing the only access. The large building on the left was cracked by the 1964 quake, and abandoned.

From Whittier, the only way on – for people and vehicles – is on the train, through the two tunnels to Portage. After the tunnels, there are views of Portage Lake and Glacier, before the railway crosses wetland on the sediment fill at the head of Turnagain Arm fiord. The forest subsided 2.5 m in the 1964 earthquake (partly due to tectonic warping and partly due to vibration compaction of the sediment), and was killed by the resultant saltwater incursion. A few houses remain half-drowned; the railway was regraded. The train unloads at Portage, from where Anchorage is reached via a good road along Turnagain Arm.

The Anchorage landslides of the 1964 earthquake

Anchorage is a sprawling city built on sediment terraces at the head of Cook Inlet. Though it lies 125 km from the 1964 earthquake epicentre, it suffered severe damage when its unstable soils were disturbed (Hansen, 1965). The city stands on hundreds of metres of unconsolidated Tertiary and Quaternary sediments. The top 6 m beneath the city are late Wisconsinan outwash gravels, sands and silts, isostaticly uplifted following deglaciation. Beneath these is the marine Bootlegger Cove Clay, more than 20 m thick and reaching to below sea-level; this is also Wisconsinan. Within this there is a layer, close to sea-level, which has a very porous, but impermeable, very fine-grained structure which is sensitive. When a sensitive clay is disturbed, it restructures and loses most of its strength as the load on it is taken by its porewater until it is drained; this loss of strength is so great that the clay behaves as a liquid – it liquefies. The earthquake vibrations caused this liquefaction to occur; as a result, huge sections of ground along the terrace edges failed in massive translation landslides (Fig. 13).

The Government Hill Landslide spectacularly destroyed a school (empty for the Good Friday holiday) on the north side of Ship Creek (Updike, Dearborn, Ulery & Weir, 1984). Its structure was typical, with displaced blocks of the gravel, grabens at its head and a debris flow at its toe. The ground has now been landscaped, though the main downfaulted graben is still recognizable.

The Fourth Avenue Landslide destroyed a large part of the downtown, leaving a step 10 m high at the junction of 4th Avenue and C Street. To allow rebuilding on the site

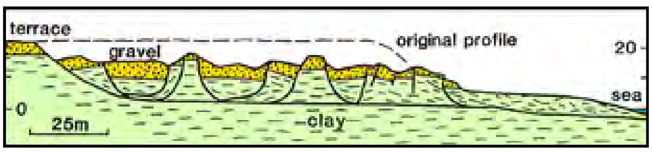

Fig. 13. Diagrammatic profile through one of the translation slides which disturbed the terraces in Anchorage during the 1964 earthquake.

a massive earth buttress was placed along the slide scar – this includes the grassy bank north of the Holiday Inn.

The L Street Landslide destroyed houses along the coast between 3rd and 10th Avenues at the west edge of town. New houses now cover most of the slide mass, and the main head scar is the steep descent on 5th Avenue just beyond L Street.

The Turnagain Heights Landslide was the largest of all, wrecking numerous houses. It is on the coast north of the airport at Earthquake Park, now a wilderness with no building remains, though ground fissures and grabens can be found along the woodland trails.

North from Anchorage to Denali

The road north to Denali is largely over vast extents of glaciofluvial debris at the head of Cook Inlet and the up the Susitna and Chulitna valleys. Bedrock is rarely seen, and even the sediments are hidden beneath forest and tundra.

After Eklutna, a bridge crosses the braided channels of the Knik River. Until 1967, this river had an annual summer flood when flow increased a thousand-fold for about 10 days. This was because the Knik Glacier extended across and dammed a valley; in summer, ponded meltwater raised the level of Lake George 50 m behind the ice barrier (Fig. 11). The pressure of water was then enough for it to force its way under the ice, and then scour and collapse a gorge through the end of the glacier – and almost drain the lake. Every year, the flood pulse damaged the river bridges, and the railway company included annual bridge repairs in its budget. Since 1967 the glacier has thinned so much that it cannot dam the lake.

Much further north, Denali and its southern glaciers may be seen from signposted viewpoints. The road crosses a broad saddle in the tundra, and then descends the Nenana River valley. There is a spectacular roadcut through a terrace of coarse cobble beds just before Denali Park Village. Through and beyond the village, the Nenana gorge is cut into crumpled and faulted Precambrian schists (Fig. 14). A slide area exposes chlorite schists with many shear zones on faults.

Out of the gorge, a right turn between the motels in Healy continues down through terraces of Pleistocene outwash to the Nenana River which is cut into dipping Miocene sands with thick coal seams. Across the river bridge, the dirt road

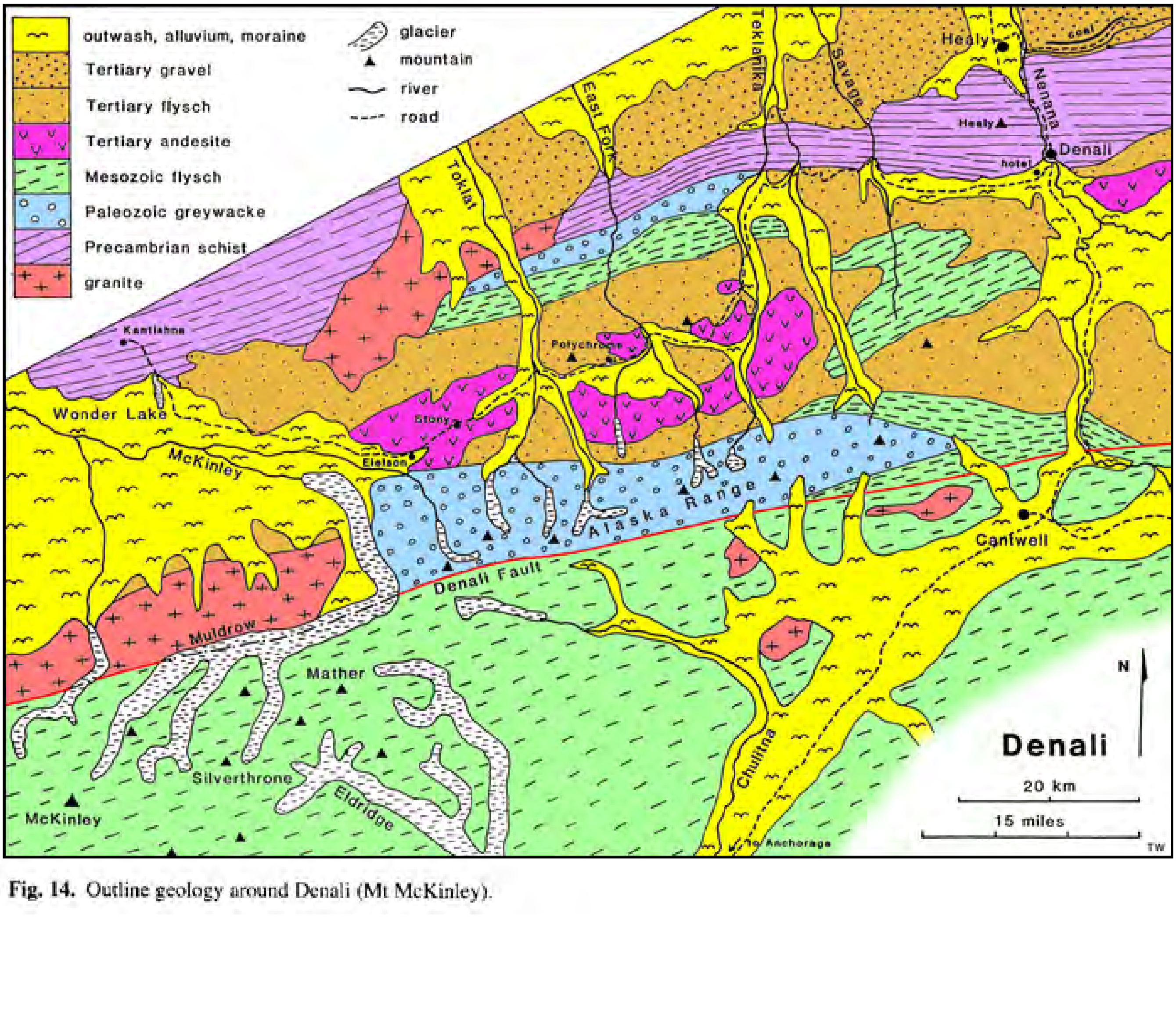

Fig. 14. Outline geology around Denali (Mt McKinley).

Fig. 15. Miocene coal measures along Healy Creek.

leaves the Usibelli coal mine on the left and heads up beside Healy Creek. Bluffs expose coal measures dipping at 40° into the cliff face; they are poorly consolidated sands and gravels with many channel structures and large chunks of coal which are fossilized tree trunks. Deposition was in braided river channels in a subsiding basin which pre-dated the uplift of the Alaska Range (Wahrhaftig, 1987); comparison may be made with the modern river and stranded tree trunks on the opposite side of the road. The warmer Tertiary climate allowed more tree growth to form the coal seams up to 5 m thick, exposed further along the road; the coal is soft and friable, and sub-bituminous, only a little more coalified than a lignite (Fig. 15).

Denali National Park

The park road along the north side of the mountains is only open to tour and shuttle buses west of Savage River; these must be booked in advance. The prime attraction of the park is the superb wildlife viewing, but there are some geological sights on the sidelines. The buses stop on demand, usually to see bears or other large game, and also at critical viewpoints.

The first stop is for a distant view of Mt McKinley – though the summit is hidden in cloud for two days out of three. McKinley (also known by its Athabascan Indian name of Denali, meaning the 'High One') reaches 6194 m, the highest peak in North America. Its elevation over the 1000–1500 m of the adjacent foothills and valleys makes it exceptionally spectacular. It stands in a long range of snowy peaks, which feeds dozens of glaciers. The main peaks are formed of metamorphosed Palaeozoic and Mesozoic flysch intruded by Mesozoic granite; the Denali Fault lies just north of the main crest separating the Mesozoic flysch from another granite block (Fig. 14). With the early Tertiary flysch and andesite volcanics on the north slopes, and late Tertiary molasse away to the north, the whole range is a microcosm of an orogenic belt. Bare rocks on the ridge to the north are Precambrian schists overlying a major thrust which crops out under the sediment along the road line.

After crossing the Sanctuary River, spruce trees are seen leaning in over small ponds, undercut not by stream erosion but by the pondwater melting the permafrost. The climb up to Polychrome Pass gives views of small kettle holes in sheet moraine, and the stop on the Pass overlooks a magnificent panorama of braided rivers on fans of outwash gravels spread below distant glaciers and mountains; coarse buff sandstone within the Tertiary flysch is exposed on the ridge.

Tour buses turn round at the Stony Hill Overlook. This gives a closer view of Mt McKinley, still 57 km away but looking a lot closer. There are excellent solifluction lobes and old rock glaciers on the slope ahead to the right (and more solifluction and landslides in the Stony Creek valley just back to the east). If the shuttle buses are being used, the Eielson Visitor Centre overlooks a beautiful tundra with opportunities to hike nearer to the mountains. The road beyond passes close to the lower part of the Muldrow Glacier which is shrouded in ablation moraine so thick that it supports a scrub vegetation while it is still moving.

South from Anchorage to Seward

The road south retraces the route to Portage, passing a turnout and display at Beluga Point on Turnagain Arm, where a modest tidal bore may be seen when the moon is favourable. The roadcut and display blocks are of Mesozoic melange, with large blocks of different rock types mangled up on a subducting plate boundary.

Portage Glacier is fed from a small icefield on the mountains south of Whittier (Fig. 11). Its advance during the Little Ice Age formed the terminal moraine on which now stands the visitor centre. The glacier is in rapid retreat; the terminal moraine now dams a proglacial lake 5 km long (and up to 250 m deep), which is the length of ice retreat since the glacier last stood against the moraine around AD 1900. The glacier front can now only just be seen from the visitor centre, but it does calve off substantial blue icebergs, which drift down the lake in spectacular style. The nearby Byron Glacier is reached by a path through alder scrub up a side valley; the meltwater river emerges from a large cave mouth in a snow cone fed by spring avalanches from the cliffs above.

The road to Seward cuts through the tail end of the Chugach Mountains which form the eastern half of the Kenai Peninsula. It follows glaciated troughs flanked by high hanging valleys, with folded but very unexciting Cretaceous and Jurassic greywacke and slate exposed in only a few cuttings.

Exit Glacier is reached up a side road just before Seward (Fig. 16). It flows 5 km from the Harding Icefield, 750 m above and 1800 km^2 in extent. It is largely clean blue ice, with narrow lateral moraines and a small proglacial outwash plain. The ice toe rides up over the sediment, clearly demonstrating the concept of a push-moraine. The greywacke outcrops by the snout reveal repetitive graded

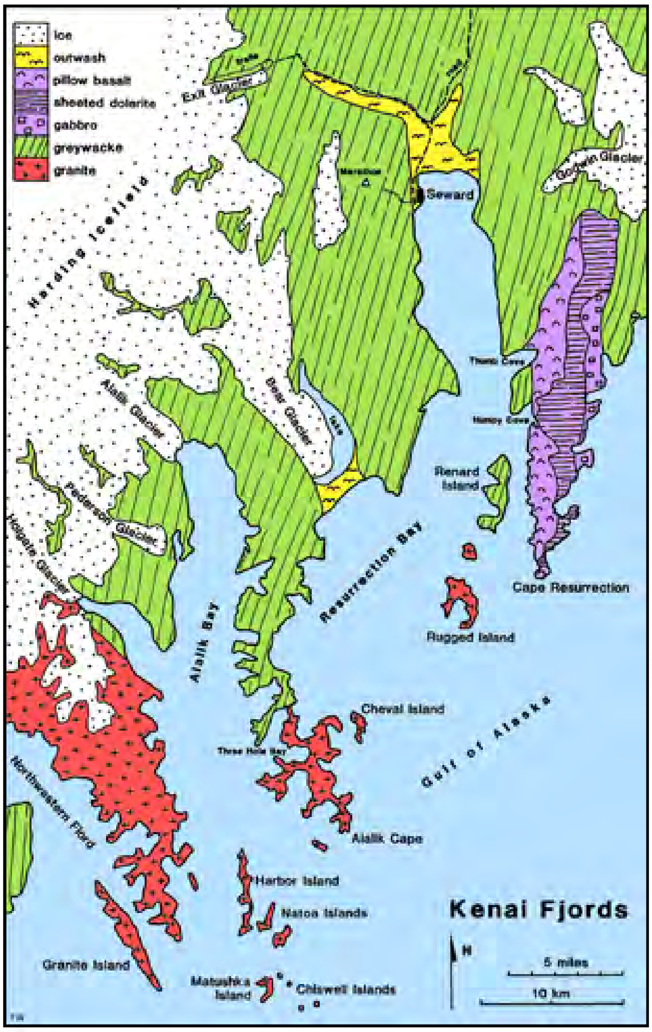

Fig. 16. Outline geology of the Kenai Fiords.

bedding; they have been overridden and rounded by the ice, and are well striated in places.

Seward was devastated by the 1964 earthquake. The town stands on an alluvial fan delta at the mouth of Lowell Creek; the fan sediment is coarse but becomes much finer offshore where steep slopes drop into water 100 m deep. The earthquake caused 3–4 minutes of strong ground motion at Seward; during this period, the finer sediments lost most of their strength, liquified, and flowed into the bay as a series of submarine landslides, and these evolved into turbidites. The front of the town, along with the harbour, docks and railway yard, slipped into the sea; some damaged structures remain at the south end of 4th Avenue, where it is clear that a flowslide took the ground from beneath the harbour rail tracks.

Kenai Fiords National Park

Almost the only way to visit the fiords is by boat from Seward; the regular tours are mainly designed to view the marine wildlife, notably whales, sea otters and innumerable birds, but they include some very fine geological features.

The bedrock of the fiords is mostly unexciting Cretaceous greywackes, except along Resurrection Peninsula on the eastern side of the Bay, where a slice of ocean-floor ophiolite has been thrust up to form a dark ridge with good foreshore exposures (Fig. 16). The ophiolite consists of the classic three-layer sequence – gabbro and serpentine below, parallel vertical sheeted dykes of dolerite in the middle, and pillow lavas of basalt on top (Tysdal, Case, Winkler & Clark, 1977). These represent the three structural types of emplacement of basic material, all of similar composition, at a divergent plate boundary. Spectacular pillow lavas are seen where the boat comes very close to shore (mainly to see the sea lions) down most of the peninsula coast south of Thumb Cove, and sheeted dykes may be recognized above Humpy Cove.

Renard Island is banded greywacke, with a drowned forest round the foreshore due to a metre of subsidence during the 1964 earthquake subsidence; Rugged Island is an Eocene granite. The Aialik Peninsula has a deeply indented coastline cut in Cretaceous greywackes with a granite on the southern tip. Its outline traces a series of drowned cirques cut by late Devensian glaciers; the cirques were submerged by the post-glacial rise in sea-level, aided by tectonic subsidence associated with the plate boundary subduction; these movements far exceeded any isostatic uplift after deglaciation.

West of the headland, Aialik Bay is another deep fiord, with its head closer to the Harding Icefield and three glaciers descending to sea-level. Holgate Glacier, on the west side of the bay, is now calving into the head of its narrow steep-sided tributary fiord. The ice front has retreated 800 m in the last 80 years, leaving a trim line in the forest on the east shore; it probably extended 8 km to the mouth of its fiord in the Little Ice Age. The high ice wall regularly calves blocks of ice which crash into the fiord, and its margins reveal clear sections through the ice and moraine. The ice retreat has exposed a perfectly profiled roche moutonnée, now half submerged in the fiord.

West from Anchorage to Katmai

The only way to Katmai is by air. The flight is down the length of Cook Inlet, a downfaulted basin of Jurassic sedimentary rocks which yield oil. To the southeast lie the moraine lowlands of the western Kenai Peninsula. To the northwest lie the snowy peaks of the Alaska Range, including Denali and Mt Spurr. The latter is a conical volcano which erupted in 1991 with an ash plume rising 8000 m, causing the temporary closure of Anchorage airport.

The flight route then goes between Redoubt and Iliamna (Fig. 3). These are two of the andesitic composite volcanoes which form the line of beautiful conical peaks along the length of the Aleutian island arc. Redoubt (3108 m) is seen first, on the right, and then Iliamna (3083 m) is on the left. Redoubt last erupted in 1989–91. An early explosion created a high ash plume; a Boeing 747 flew into it at a height of 8000 m, and lost power in all four engines - so that the plane fell 5000 m in 8 minutes, before the engines were restarted for a safe landing. Subsequently a lava dome grew in the crater, before being destroyed by another vertical blast sending an ash cloud up to a height of 15 km. There was also a huge mudflow into the valley to the north, and milder explosive activity continued for another 15 months. Iliamna is less active, except for almost continuous summit fumarole steaming. The next volcano, Augustine, is an island cone 1258 m high which erupted last in 1986, with violent explosions, pyroclastic flows, mudflows and a huge ash cloud.

The flight then heads inland across the taiga and tundra to King Salmon airport, from where a float-plane is needed for the short flight to the Katmai National Park. This flight is at low level over taiga with thin stands of white spruce; it is a low terrane of moraine and outwash, with shallow lakes and meandering rivers. The plane lands on the lake beside Brooks Lodge – almost the only place to stay in the park, and the key to reaching Katmai.

Brooks Lodge is special. It is the only place in the world where groups of people and bears live together in harmony. The Alaskan brown bears are the same species as grizzlies, but are much larger due to their rich diet of abundant salmon; by the end of summer they have grown to about half a ton, ready for their enforced winter fast. The bears live at Brooks and feed on the salmon, and don't want to bother humans – as long as the humans don't bother them or encroach into their space. Human encounters with bears must always prompt an immediate slow retreat – by the human. Because visitors do exercise due respect, bear attacks are almost unknown at Brooks.

Bear watching is the main attraction at Brooks, and is not difficult. Bears often wander between the cabins at the lodge – and add a little spice to the late night return from the bar. The best bear viewing is at Brooks Falls, reached by a short walk through a beautiful forest. The falls are about 1.5 m high over a rock sill of Tertiary bedded andesitic tuff. They are one of Alaska's top bear locations, because of the excellent fishing opportunities which they provide. In July, the red sockeye salmon come up the Brooks River by the thousand, to spawn in the feeder streams of Brooks Lake. As the salmon leap up the waterfall, the bears wait to catch them, often in mid-air. It is a great spectacle, but in July the area is seething with day-tripper tourists and hungry mosquitoes. In August, the salmon are fewer, and the bears go up into the hills to feed on berries. Then in September, there is a smaller run of the silver coho salmon, and many dying red salmon drift back downstream; the fishing is good and the bears return to the river for a last big feed. In either season it is a truly memorable spectacle. Once sated with the wildlife, the visiting geologist can return to the volcanic attractions.

Katmai Volcano

The 56 active volcanoes of the Aleutian chain are the spectacular expression of the convergent plate boundary beneath them. The oceanic Pacific plate is moving northwest to be subducted beneath the continental crust of Alaska, on the American plate, creating the mountain chain and the andesite rhyolite volcanoes. Further west, the Pacific plate dives beneath an oceanic section of the American plate, flooring the Bering Basin, and so only an island arc of explosive volcanoes is forming. Within this great chain, Katmai is one of a close group of six very active explosive volcanoes.

In 1912, Katmai burst into activity with five days of earthquakes and explosions, which were fortunately enough to encourage the native population of Katmai village, on the south coast, to move well away. The high plinian eruption columns deposited thin airfall ash over a wide area. Then on June 6 and 7, there was an unprecedented series of massive explosions, which were heard as far away as Juneau.

The explosions were accompanied by a sequence of pyroclastic flows as a huge volume of incandescent rhyolitic pumice was extruded (Hildreth, 1983). Most of this went down the Ukak River valley, which then became the Valley of Ten Thousand Smokes (Fig. 17). Other ash flows went down the Katmai River valley to the south; but these were more like surges, with more gas and less solids; they incinerated trees as far away as the coast, and their acidic fumes left the ghost forest near the abandoned site of Katmai village.

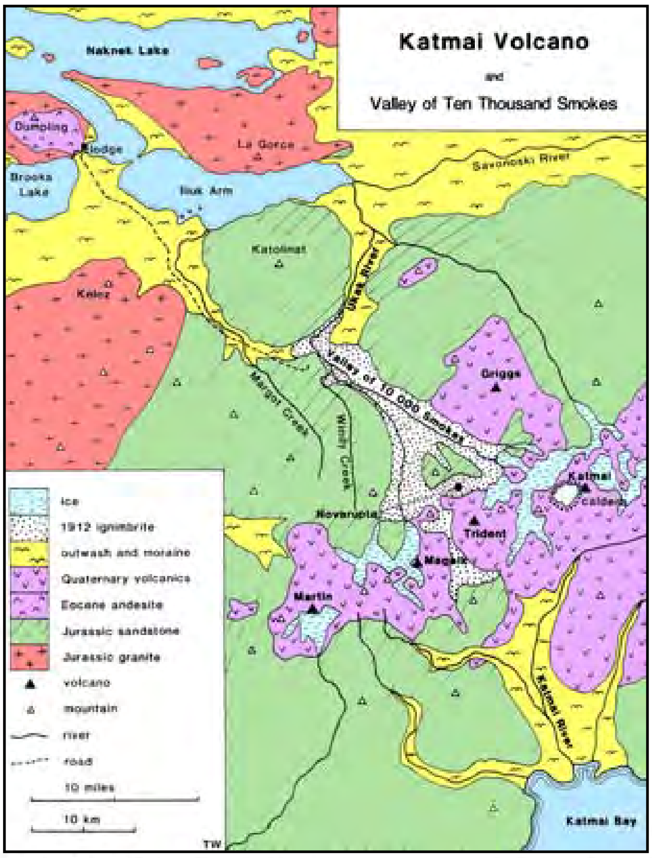

Fig. 17. Outline geology of Katmai and its related volcanic features.

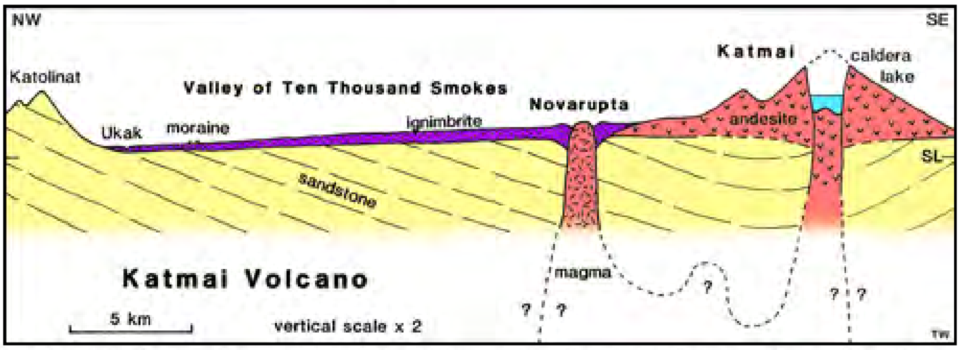

Fig. 18. Cross-section through Katmai, Novarupta and the Valley of Ten Thousand Smokes. The profile of the magma chamber is conjectural.

Following the violent pyroclastic flows, plinian eruptions hurled ash into the upper atmosphere. The resultant airfall deposits were thickest downwind to the southeast; they were a metre thick on the south coast, created two days of darkness as they landed on Kodiak, fell noticeably on Seattle, and left the finest material to circle the world in the upper atmosphere and reduce surface temperatures for a year.

All this ash had not emerged from the Katmai volcanic cone. Instead, it had emerged from a great new vent 10 km to the west, and from adjacent fissures. The new vent was subsequently known as Novarupta; it was essentially a flank eruption of the Katmai volcano. As the magma exploded out of Novarupta, more magma flowed west underground, almost emptying the interior of Katmai. Consequently the summit of Katmai collapsed into a huge caldera. Nearly 300 m of the summit disappeared, and was replaced by a caldera over 600 m deep and 3 km across (Fig. 18). The final stages of the eruption saw a rhyolite dome block Novarupta, where it now sits within an ash ring, thrown out by the dying gassy blasts (Fig. 19). At Katmai, a small dacite lava dome formed on the caldera floor; it is now drowned beneath a lake whose level is 200 m above the dome and continues to rise a few metres each year. The lake rarely freezes over because of its underfloor heating, and its level will stabilise when the permeability of the caldera walls matches the snowmelt input.

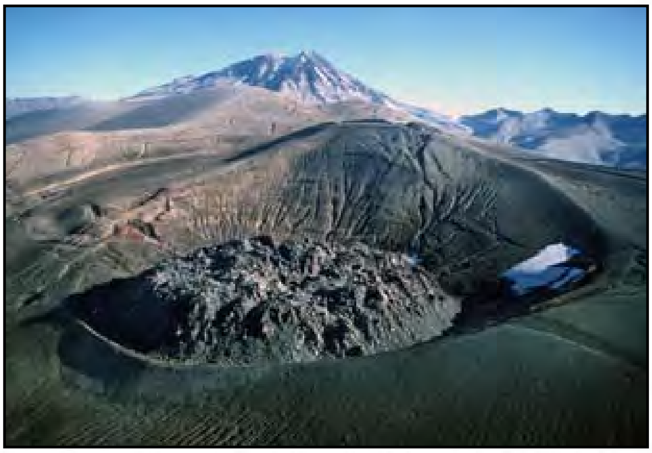

Fig. 19. The lava dome at Novarupta, with Griggs volcano behind.

About 30 km^3 of debris was erupted in the 1912 event. Roughly half of this was effectively replaced by the collapse of the Katmai caldera. The rest must be accounted for by a quite small Novarupta collapse, expanding gases which caused the very high porosity of the pumice debris, any broader surface deflation of the volcano, and then any new magma that rose from below.

In the main stage of the eruption, pyroclastic flows filled the Ukak River valley to a depth of 200 m, reaching 22 km down the valley, and creating a new floor up to 5 km wide (Hildreth, 1983). This was the new Valley of Ten Thousand Smokes. About 12 km^3 of pumice filled the valley in roughly 20 hours. It was at a temperature of over 500°C, and emerged in a sequence of surges; some of it welded as it settled – the ignimbrite varies in texture from a loose sand to a totally welded glass. At the top of the valley, the flows probably moved rapidly, but then slowed to a sluggish pace such that they were almost dammed and halted by a terminal moraine near their terminus.

The scale of the eruption was such that nobody who saw it could have survived – which is unfortunate, because this is the only significant ignimbrite to have been erupted in historical times. Though its material is not welded into a completely solid mass, no other historical pyroclastic flow has had such a high density with such a high solid-to-gas ratio. Comparable ignimbrites are only found as prehistoric deposits, such as those in Yellowstone Park. The enormous volume of the Novarupta deposit also meant that it changed composition through its eruption, as new magma moved underground to refill the emptying magma chamber beneath the volcanic vent. The lower part of the ignimbrite contains mainly rhyolitic fragments from the viscous magma plug which had grown beneath Novarupta before 1912; but the upper part has more andesitic material which flowed in from beneath Katmai, replenishing Novarupta and allowing the Katmai caldera to collapse.

The Valley of Ten Thousand Smokes was first seen by the Griggs expedition in 1916 (Griggs, 1922). They saw a fantastic panorama of steam jets, some rising 150 m, and so gave the valley its name. The steam originated from groundwater in the alluvial gravels which had been buried and boiled by the ignimbrite. This is similar to the processes behind the rootless craters of Iceland and elsewhere, except that the rising steam could not carry much sediment up through the cohesive ignimbrite of Katmai; almost none of the valley vents has built a cone. As the valley ash deposits cooled, the steam vents had to die down. Return expeditions in the 1930s found greatly reduced activity, and today none of the valley floor vents still steams. The only active fumaroles are those up on the volcanoes with deep-seated sources of steam. Down in the valley the ash flow ignimbrite is cold, and has now been eroded by the meltwater streams from the Katmai glaciers; a series of spectacular canyons reveals splendid sections through the pyroclastic deposits.

The Valley of Ten Thousand Smokes

The valley is most easily reached on a bus excursion which leaves daily from Brooks. The bus heads southeast on a dirt road through a forest of spruce, birch, alder and willow (Fig. 17). It stops at the Iliuk Arm overlook; moraines include the breached terminal across Naknek lake; Jurassic granite on the far side of the lake is faulted against Jurassic sandstones forming Mt Katolinat on the near side. The bus continues to the end of the road at Overlook Cabin.

The cabin is at an elevation of 400 m, on a hill of poorly exposed Jurassic sandstone, overlooking the Valley of Ten Thousand Smokes 200 m below. The valley floor with the buff ignimbrite is spectacular, flat except where cut into by post-eruption rivers. A terminal moraine lies across the valley just below the cabin; the ash flow banked up against this, and only flowed through the old breach to feed its narrower continuation below the moraine. Charred tree stumps can be seen on the moraine close to the edge of the ash flow, where dunes of wind-blown ash are building on the lee of the ridge.

Katmai is famous for its foul weather (though the valley fares better in the rain shadow), and the view to the head of the valley is usually lost into cloud, while swirling dust clouds blow up from the exposed ash. Mt Griggs, north of the valley, has active solfataras on its summit. Katmai is straight up the valley, above and beyond the glaciers which usually show beneath the cloud. Novarupta is just out of sight, behind a sandstone bluff.

A good trail leads to the valley floor, with changing views across the ignimbrite plain and its river canyons. Exposures beside the Ukak River are of Jurassic sandstone containing plant fossils, small fragile lamellibranchs and mud pellets; ignimbrite in the bank contains mainly dacite pumice fragments, and also darker country rock and andesite.

The trail to the north continues to the best viewpoint, where the river cascades through a ravine in the sandstone. Above it, the ignimbrite has been cut into a vertical wall over 20 m high. The material is crudely banded, due to pulsing surges within the original pyroclastic flow. Most of the pumice sediment is fine grained, but included blocks up to half a metre across indicate the violent turbulence within the flow; a basal layer of coarser debris represents a bottom load transported by saltation over the ground instead of suspension within the gas cloud. The top metre of the cliff is finely layered airfall ash. There are two exposed fumarole pipes. These were the sites of steam vents (the Smokes) where boiled groundwater escaped upwards; they are now backfilled by slumped ash; there is some hydrothermal discoloration, but the steam has had little influence on the modest level of lithification of the ignimbrite.

A trail to the south stays near the river, opposite the moraine bank, giving improving views of the ignimbrite cliffs, revealing various channel and compaction structures in the ash flows. Some exposures very close to the trail allow inspection of the pumice debris, and a small remnant pillar of ignimbrite remains where it was indurated beneath a steam vent. The trail ends at a viewpoint over Three Forks, where three spectacular canyons converge within the ignimbrite (Fig. 20). Where the east wall of the main canyon curves out of sight, it exposes a bank of moraine

Fig. 20. The 1912 ignimbrite exposed in the 25 m high river cliffs at Three Forks in the Valley of Ten Thousand Smokes; the dark bank beyond the river on the right is cut into glacial till capped by a layer of charred vegetation.

Fig. 21. Steam emerging from the summit crater of Martin.

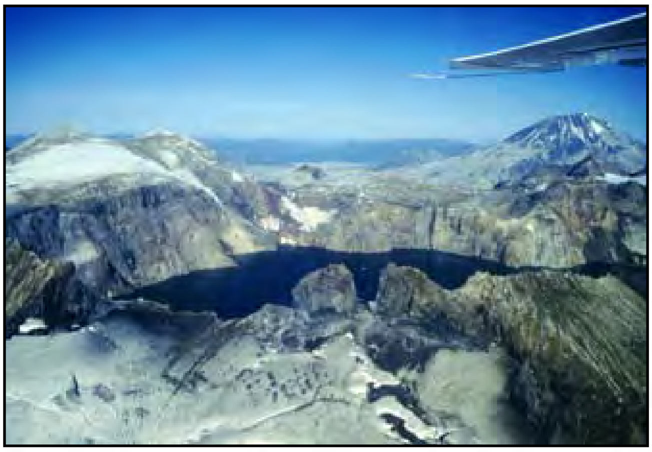

Fig. 22. The Katmai caldera, created in 1912; the Valley of Ten Thousand Smokes is in the middle distance.

beneath the ignimbrite and this is capped by a dark layer of pre-eruption soil and organic debris charred by the hot flow gases.

The other way to appreciate the volcanic features of the region is from the air. Flightseeing can be arranged at Brooks Lodge, but the normally foul weather on the mountains means that this is only feasible on a few days of each year. When possible, the planes fly straight up the Valley of Ten Thousand Smokes and then loop round the volcanoes. Martin has a large steaming summit crater (Fig. 21); Mageik is snow-capped and dormant; Novarupta still has its fractured lava dome surrounded by the ring of explosion debris; Trident is draped with flows of viscous lava dating from 1953 and reaching out over the 1912 ignimbrite. Most spectacular of all, the Katmai caldera has a knife-edge rim whose wall exposes bedded volcanics and dykes (Fig. 22); small glaciers now hang inside the caldera walls, but there is no ice on the lake – its water is still warm and its deep green hue is broken only by patches of sulphurous froth.

With or without a flight over the volcanoes, a visit to Brooks Lodge and Katmai is a unique experience. It is a geological gem, and should be the highlight of any geological tour to the splendours of Alaska.

ACKNOWLEDGEMENTS

The author records his thanks to the Nottingham Trent University for support and facilities; to Beryl Whittaker of Nottingham, Mike Bamlett of Birkbeck College and Eric Robinson of the Geologists' Association for prompting him to run the Alaska tour; to his wife Jan for invaluable help on the 1993 recce; and to Judy Rigby for admirable assistance on the 1994 tour. This guide has drawn from a great number of maps and publications by innumerable American and Canadian geologists – to whom the credit for unravelling the geology of these northern lands truly belongs.

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