Yukon placer diamonds: Possible sources

by Yana Fedortchouk
Yukon Geological Survey

Diamond placer occurrences are historically reported in Yukon and in the adjacent areas of British Columbia and Alaska (Casselman and Harris, 2002) and are generally recovered during clean-ups on placer gold mining operations. While three stones from Crooked Creek in Alaska have been scientifically confirmed and described (Forbes *et al*., 1987), the same cannot be said of the Yukon diamond placer occurrences. In the Yukon, reports of a diamond discovery initiated sampling for diamond-indicator minerals that subsequently returned neither diamonds nor their indicators (chrome-diopside, pyrope-garnet, picro-ilmenite). Furthermore, none of the known ultramafic rocks, diatremes of ultramafic-alkaline volcanic rocks nor high-pressure eclogites in Yukon and Alaska have been proven to be diamond-bearing. Alluvial diamonds are present along the West Coast in Oregon and California (Hausel, 1994) and exploration of diamond placers in California produced several hundred stones, including high-quality gems. However, all of these aforementioned occurrences lack diamond-indicator minerals common for cratonic diamond deposits, and no igneous diamond-bearing rocks are known in the area. Therefore, the placer occurrence of diamonds in Yukon as well the Pacific Coast remains enigmatic.

Conventional and unconventional diamond sources

Most economic diamond deposits in the world have been identified on Archean cratons, the oldest and most stable parts of the continents. At the base of these continental nucleuses, in a high-pressure region (approximately 200 km deep), temperatures are lower than in the younger mobile belts and this creates an environment allowing diamonds to be stable. Kimberlites and other deep-seated magmas which originate in the mantle ascend to the Earth's surface and provide transportation for diamonds and other deep mantle minerals (such as diamond-indicator minerals). The mantle outside of the cratonic areas is believed to be too hot to contain diamonds.

Geologically, Yukon is located outside of the North American craton in a mobile belt with Paleozoic and Mesozoic tectonic activity. It is, therefore, not in a conventional setting for diamond deposits, in contrast to the Northwest Territories. Glacial transportation of diamonds from the North American craton into Yukon is generally not supported, as there were no glaciations in many of the areas of Yukon with reported diamond occurrences (Canil *et al*., 2005, and references therein). Another possibility explaining the presence of diamonds in the Yukon is the preservation of diamondiferous fragments of the cratonic keel in the Cordillerian lithospheric mantle sampled by kimberlites and other deep-seated magmas (Simandl, 2004). However, this is not probable due to the absence of igneous diamond-bearing rocks in the area and lack of diamond-indicator minerals in detritus. The location of Yukon and Pacific Coast placer diamond occurrences outside of the craton in the tectonically active zone, absence of diamond-bearing igneous sources, and lack of conventional diamond-indicator minerals has led to the search for another mechanism of diamond formation, which is different from that in cratonic keel settings.

Diamond formation in a oceanic plate undergoing subduction was proposed by a number of researchers (e.g., Hausel, 1994; Griffin *et al*., 2000; Simandl, 2004). Very low temperatures in the down-going slab promote diamond stability at lower pressures and at a notably shallower depth (~ 100 km) than in the cratonic mantle (~150-200 km)

[1]*yana.fedortchouk@gov.yk.ca*

(Simandl, 2004). During plate collision, some of these diamondiferous parts of the oceanic plate might have been tectonically emplaced on the Earth's surface. Obducted ophiolites along the North American plate margin were proposed as a possible source for the alluvial diamonds in California (Hausel, 1994). Such diamond occurrences in chromite lenses of alpine-type peridotites have been identified in few locations around the world including Morocco, Spain and Tibet (Griffin *et al.*, 2000, and references therein). Erosion of these massifs would produce alluvial diamonds accompanied only by chromites.

Tectonic uplift of ultrahigh pressure (UHP) crustal metamorphic rocks during continent-continent collision is known to produce massifs with diamondiferous eclogites and gneisses, such as Kokchetav massif (Kazakhstan) and massifs in China and Western Norway (Griffin *et al.*, 2002, and references therein). Detrital clinopyroxenes and garnets with composition similar to the UHP massifs were found in the Atlin area, Northern BC and are proposed to be derived from a possible UHP source for the Wilson Creek diamond reported in the Atlin area (Canil *et al*, 2005). However, all diamonds found in tectonically uplifted massifs are poor quality. Crustal massifs contain only micro-diamonds which are cubic shape, commonly fibrous or partially graphitized and found as inclusions in other minerals.

Alpine-type peridotites contain some macro-diamonds, but these are completely graphitized (Griffin *et al.*, 2000). As yet, no diamonds of good quality have been confirmed to have been derived from tectonically emplaced high-pressure rocks.

In addition to being the hardest mineral, diamond is also chemically inert at the conditions of the Earth's surface and is very stable during erosion and subsequent transportation. Therefore, the absence of indicator minerals in diamond placers may also be the result of a very long alluvial history. The diamonds may have been formed at the base of the North American or some other ancient craton and then transported to the Earth's surface by ancient Precambrian magmas. Erosion of these igneous sources, followed by a long history of formation and subsequent erosion of diamond secondary collectors (such as conglomerates), would create placer deposits containing high-quality diamonds accompanied by no indicator minerals, such as those in New South Wales, Australia (Davies *et al.*, 2002). A characteristic feature of ancient diamonds that have experienced a long surface history is good quality which was resistant to breakage, and the presence of abrasion marks on the diamond surfaces as a result of transportation in large river systems (Afanasiev *et al.*, 2000 and references therein).

***Figure 1**. Origins of placer diamonds.*

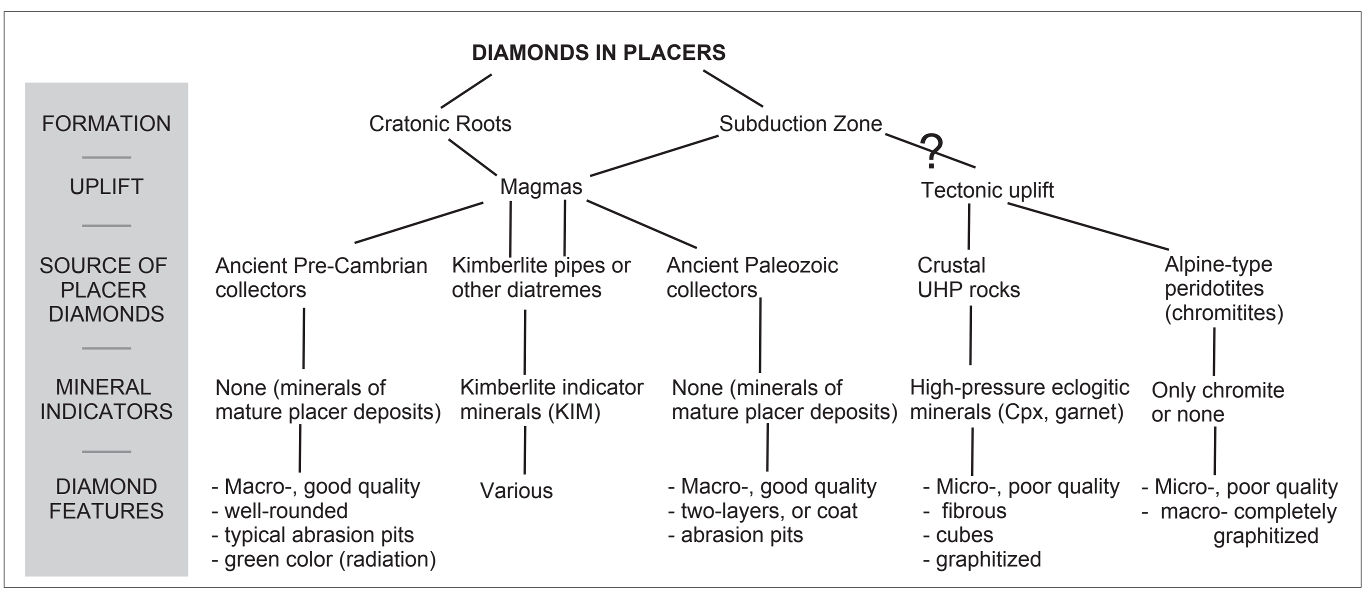


Figure 1 summarizes sources, paths, associated minerals and diamond properties of different origins for placer diamonds. The sections following describe the properties and settings of Yukon alluvial diamonds aiming to define which of the possible scenarios are the most suitable for these occurrences.

Properties of reported diamonds

Properties of diamonds (colour, morphology, surface features) reflect the conditions during their growth, method of transportation to the Earth's surface and their history at the surface. None of the diamonds recovered from placers in the area of the Pacific Coast underwent a full-scale scientific investigation that may have included studies of nitrogen content, isotope ratios and inclusion assemblage to determine their cratonic *versus* subduction origin. However, a group of diamonds from Trinity County, California and three diamonds from Circle, Alaska were well described (Kopf *et al*., 1990, Forbes *et al*., 1987). None of the Yukon diamond occurrences were well documented or confirmed. Table 1 is based on the information from Casselman and Harris (2002) that summarizes the properties of diamonds reported from Yukon and the adjacent areas of Alaska and B.C.

Nearly all of the diamonds reportedly found in Yukon were visually identified and hand-picked by placer gold miners during the clean-up of their concentrate. It is likely that most of these diamonds were macro-diamonds, transparent or nearly transparent, not fibrous or coated, and had an octahedron or rounded shape such that a lay-person would recognize them. This would be consistent with the physical features described for the diamonds found in Circle, Alaska, and Wilson Creek, B.C. This type of diamond is common in kimberlites and other diamond-bearing magmas that sampled cratonic mantle, but has never been found in tectonically emplaced massifs.

***Table 1**. Properties of diamonds reported in Yukon and adjacent areas of Alaska and BC.*

Location	Size, weight	Colour/quality	Morphology	Recovery	Surface features	References
Yukon						
Bonanza Creek, Dawson area		mounted on a ring		"showing-up" in the concentrate during clean-up		1
Clear Creek, Dawson area	6 small diamonds			grease table		1
Indian River[1], Dawson area	12 diamonds					1
Dixie Creek, Kluane area Dominion Creek and Rosebud Creek, Dawson area						1
British Columbia						
Wilson Creek	¼ inch	yellowish white	flat, rounded shape		rough surface	1
Alaska						
Canyon Creek	single diamond			cleaning placer concentrates		1
Jack Wade Creek		Tested with thermal inertia probe[2]				1
Circle Diamonds "Regan Diamond" "Warren Diamond" "Manuel Diamond"	 1/3 carat 1.4 carat 0.83 carat	 clear yellow-white light yellow	rounded octahedron deformed or pseudo-dodecahedron twinned dodecahedron	clean-up operations	numerous small, crescentic indentations small percussion marks	1, 2
Turn Creek						1

[1]C.F.Mineral Research – visual examination reported chrome-diopside, olivine and variously coloured garnets
[2]Thermal inertia probe mostly does not work for fibrous opaque diamonds

References: 1. Casselman and Harris, 2002; 2. Forbes *et al.*, 1987.

All diamond descriptions in Table 1 indicate a rough surface or the presence of percussion marks on the stones that can only be developed through a very long alluvial history as a result of mechanical abrasion (Afanasiev *et al.*, 2000). Percussion marks are believed to be a result of transportation in very large river systems — these would be much bigger than the present-day creeks containing diamonds in their alluvium. These surface features resemble percussion scars observed on alluvial diamonds from New South Wales, Australia. Located in a convergent-margin setting of Eastern Australia, these placer diamonds also lack any indication of their primary or bedrock source. They are divided into two groups: 1) Precambrian diamonds which were formed and magmatically emplaced onto one of the world's ancient cratons, and 2) diamonds which formed in a subducting slab and were transported to the surface by magmas during the late Paleozoic. Both diamond types underwent a very long surface history in secondary collectors and now occur in mature alluvium and paleo-alluvium containing ancient sediments (Davies *et al.*, 2002). This form of diamond placer is also known in other places of the world, such as the Ural Mountains in Russia (Fig. 2).

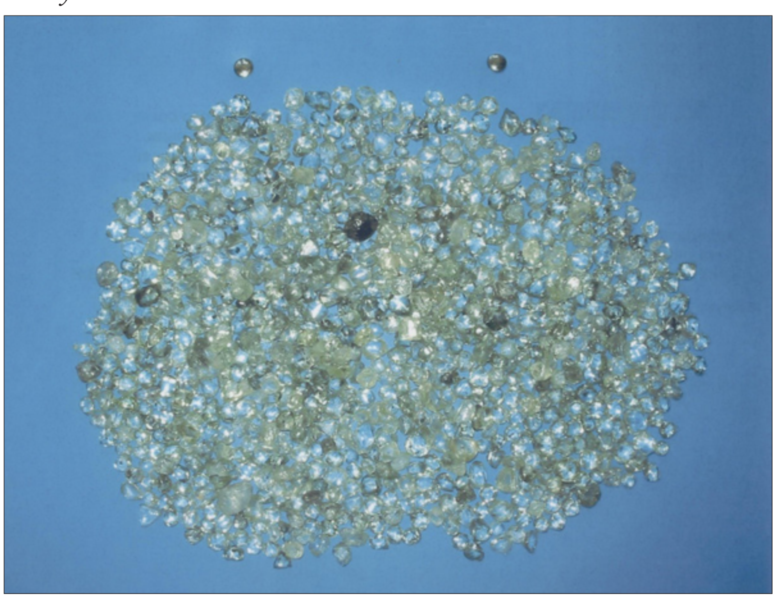
The existing diamond descriptions from placer occurrences in Alaska, B.C. and the good quality of diamonds reported in Yukon, suggest a relatively long history of equilibrium growth at the base of a craton or in a subducting slab, followed by subsequent transportation to the Earth's surface in a kimberlitic or other deep-seated magma. Rough surfaces and percussion marks suggest a long alluvial history.

Diamond-indicator minerals

Minerals, including pyrope-garnet, ilmenite and chrome-diopside, are mostly from a diamond-bearing mantle source and are known as diamond (or kimberlite)-indicator minerals. These minerals generally accompany diamonds during their transportation in kimberlite magmas to the surface, and follow them during the erosion of the kimberlite pipe and subsequent incorporation into sediments such as alluvium. These minerals are relatively resistant to chemical and mechanical weathering, and their presence in detritus indicates the possibility of a diamond occurrence. However, garnet, ilmenite and diopside are common minerals of a large variety of igneous and metamorphic rocks. Therefore, only the presence of certain elements in the mineral structure (e.g., Cr and Ca in garnet, Mg in ilmenite and Cr (Na and Al) in diopside) can be used to determine the mantle origin of these minerals. Dark green diopside, as well as purple and orange garnets, were reported from a few localities in Yukon and California, but these were only visually identified and not followed up by any chemical analyses (Casselman and Harris, 2002, Kopf *et al.*, 1990).

A detailed study of heavy-mineral concentrates from several creeks with reported diamond or diamond-indicator mineral occurrences was performed by Yukon Geological Survey in order to confirm mineral compositions and determine possible sources. The samples returned abundant garnets which were pink, orange and red in colour, as well as some grains of dark green diopside, ilmenites, chromites and few olivines. The chemical composition of these grains was determined by electron microprobe analyses at McGill University. All the analysed grains lie outside of the kimberlite field (Fig. 3) and differ from the composition of the mineral assemblage of high-pressure eclogites. Thus, the study of several hundred mineral grains revealed no diamond-indicator minerals.

***Figure 2**. Alluvial diamonds from the Ural Mountains in Russia. Note the transparency and high quality, typical of diamonds which have undergone a long transportation history.*



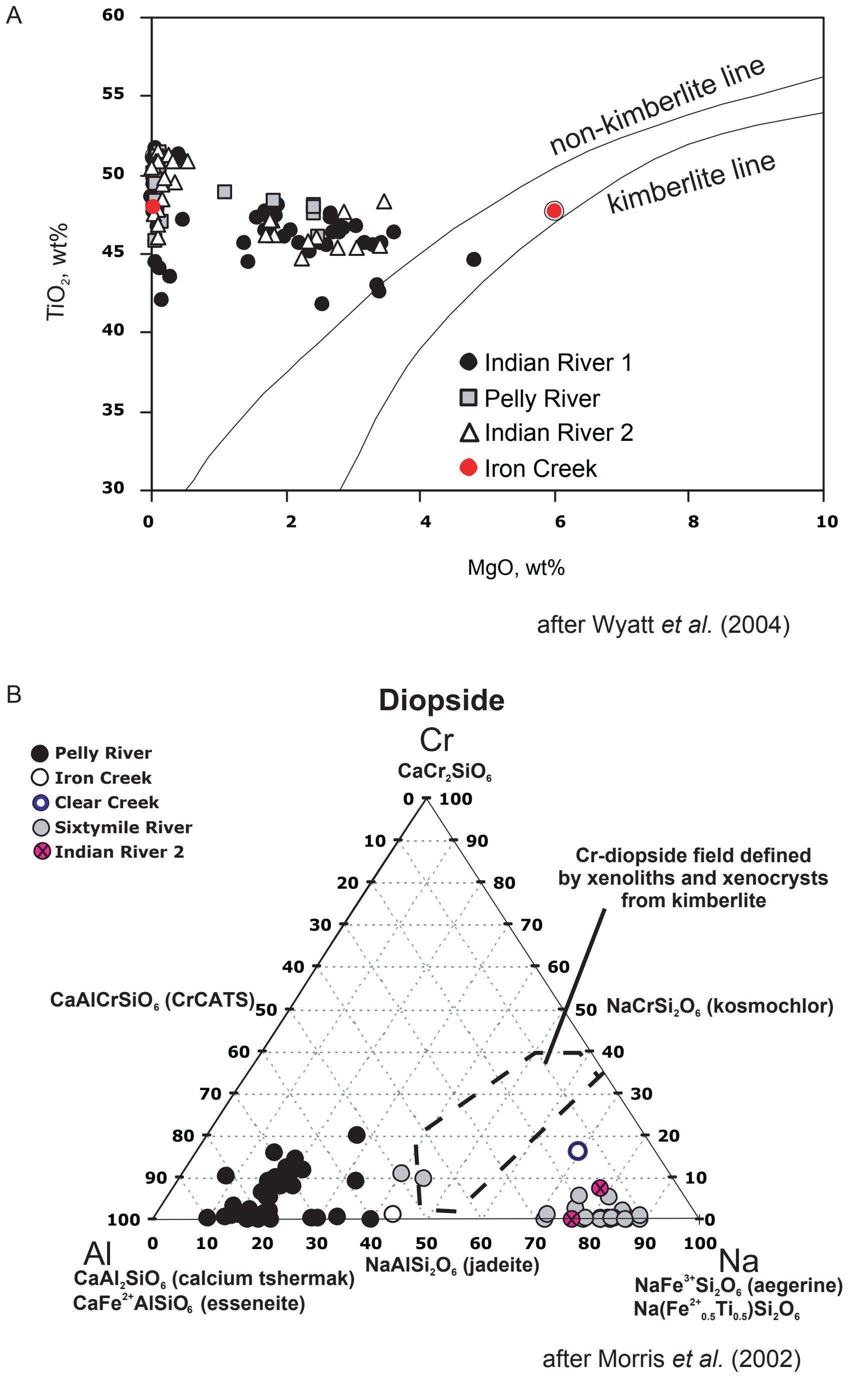


Figure 3*. Composition of ilmenites (A) and diopsides (B) from the reported diamond or diamond-indicator mineral placer occurrences (Indian River, Sixtymile River, Clear Creek Iron Creek and Pelly River) compared to the compositional fields of kimberlite-indicator minerals.*

The complete absence of diamond-indicator minerals in the alluvium from creeks with reported diamond occurrences may suggest that the diamonds have come from some ancient sources and all other mantle minerals were completely destroyed during the long alluvial history (V.P. Afanasiev, personal communication, 2007). As the mineral most stable to chemical alteration and abrasion, diamond would be the only preserved mineral in this case. It is possible that some diamond-indicator minerals in the studied samples were overlooked, but their presence is unlikely given the large number of analysed mineral grains. For that reason, formation of diamond placers from the erosion of unknown igneous rocks or high-pressure eclogites is improbable. However, placers of ancient diamonds re-deposited from paleo-alluvium originating on a craton

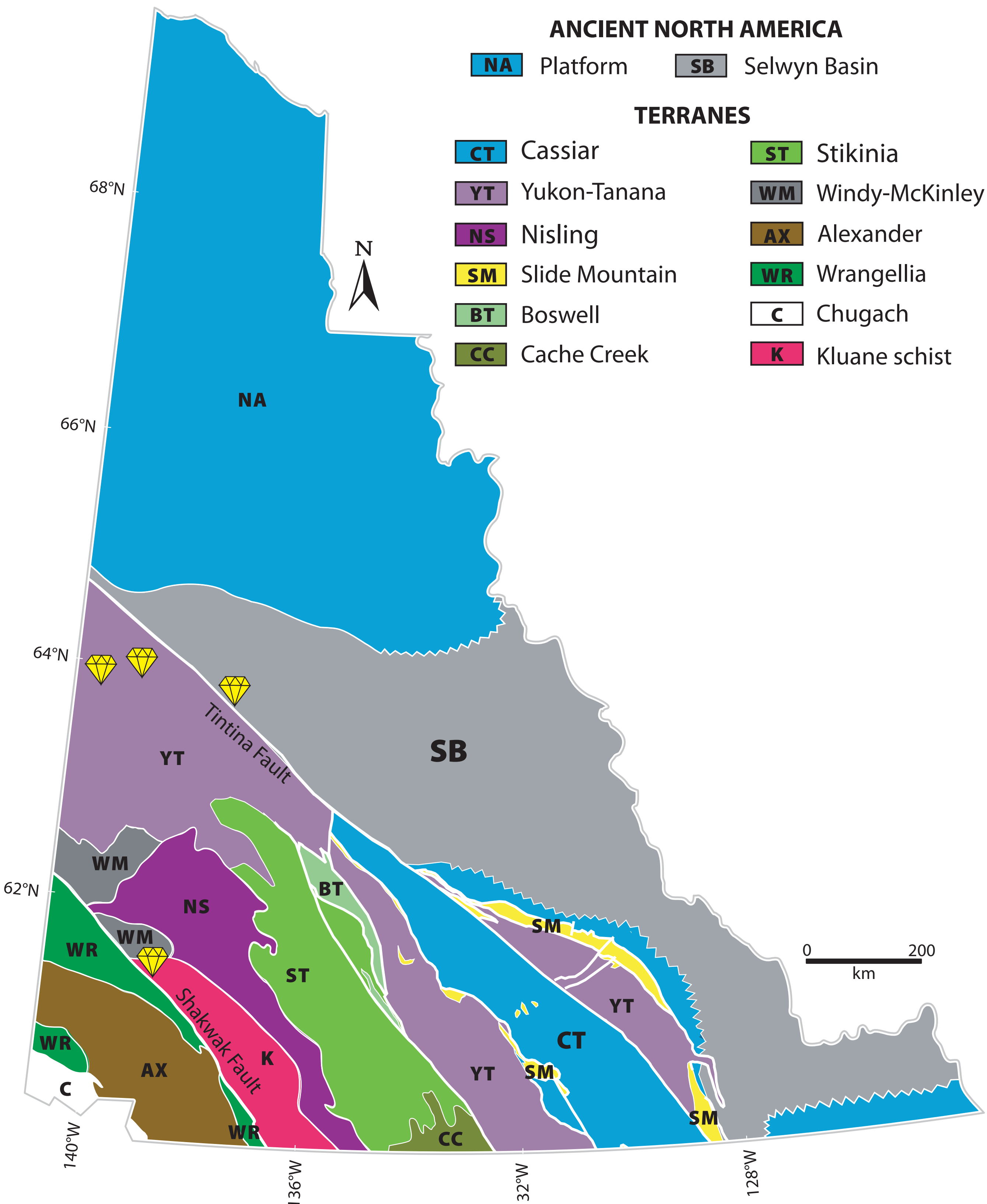


Figure 4. Geologic location of reported diamond occurrences in Yukon (terrane map is modified after Gordey and Makepeace, 2001).

and containing only minerals typical of mature placers, such as corundum, zircon and quartz, provide a more suitable explanation for the absence of any indicator minerals or diamond-bearing igneous rocks in the area. Obducted ophiolites proposed by Hausel (1994) as a diamond source in California would result in detritus with an eclogitic mineral assemblage: pink or orange garnets with elevated sodium-content and pyroxenes with high Na_2O and Al_2O_3. However, in some cases, chromite may be the only mineral of diamond-bearing alluvium derived from ophiolite; but there may be platinum associated with the assemblage.

Geologic settings of Yukon diamond occurrences

The Yukon has complex geology consisting of several terranes with very different composition, tectonic and geological history (Gordey and Makepeace, 2003, 2001; Fig. 4). The northeast part of the Territory represents a margin of the ancient North American continental craton, divided by the major Tintina Fault from younger rocks on the southwest side of the Yukon. This younger part of Yukon has a complex history of rifting, formation of ocean basins, volcanic arcs and subsequent subduction. It consists of 1) pericratonic terranes with an affinity to the North American craton, as indicated by the similarities of the composition and stratigraphy of sedimentary rocks; 2) terranes composed of oceanic floor rocks and volcanic arcs developed on the margin of North America; and 3) exotic terranes that formed very far from their present location and drifted to collide with North America, as a part of subducting oceanic plate.

Restriction of diamond placers to certain terranes may provide insight to their origin. Post-accretion kimberlite pipes or other diamond-bearing diatremes could be emplaced within different tectonic units. In contrast, obducted ophiolites, and diamond placers associated with them (Hausel, 1994), will be most likely located within oceanic terrains. Secondary collectors of ancient diamonds with a long alluvial history are expected to exist within pericratonic terranes containing redeposited sediments derived from the craton. The location of Yukon diamond occurrences within or in the immediate proximity of the pericratonic terranes (Fig. 4) favours the proposed ancient origin for the Yukon diamonds.

Summary

There are several possible sources of placer diamonds (Fig. 1). The occurrences of the Pacific Coast alluvial diamonds outside of the ancient North American craton (a typical setting for diamond deposits), and the absence of common diamond-indicator minerals and diamond-bearing igneous rocks, limit the possible sources to 1) tectonically emplaced obducted oceanic slab that underwent high-pressure and low-temperature metamorphism (Hausel, 1994, Simandl, 2004); and 2) secondary collectors of ancient diamonds uplifted during a Precambrian or Paleozoic intraplate magmatic event from their source at the base of a craton or in a deep subducting slab. The latter scenario satisfies all the existing data, including the properties of the recovered and reported diamonds, the absence of kimberlite-indicator minerals and minerals of high-pressure eclogites, and the geological position of diamond occurrences.

Prospecting for placer diamonds of ancient origin requires different methodology than prospecting for placers formed by the erosion of the conventional diamond sources, and requires a good understanding of the local geology. Such diamond occurrences are expected to happen in the proximity of sedimentary rocks that contain paleo-alluvium or elements of ancient sediments formed on the craton in, presumably, Proterozoic time. Detrital minerals that may indicate a presence of such old sediments are the minerals of mature placers – well-rounded corundum, zircon, quartz, topaz and some Al-rich minerals. Due to the large difference in the specific gravity of gold (15 – 19) *versus* diamond (3.5), the gold recovery system used by most miners is not suitable for diamond prospecting. Therefore, if diamond prospecting is to accompany gold mining, an additional extraction system that retains minerals with lower specific gravities has to be used.

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