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TEMPORAL DISTRIBUTION OF THE ULTRAMAFIC-ALKALIC AND ALKALIC ROCKS WITHIN THE RUSSIAN, SIBERIAN, AND NORTH AMERICAN ANCIENT PLATFORMS AND THEIR SURROUNDINGS

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Introduction

The temporal and spatial distribution of ultramafic-alkalic and alkalic complexes in ancient platforms may provide information on the tectonic stability of these platforms. Geochemical data derived from these complexes can lead to conclusions about global pulses of magmatic activity as well as the duration of the evolution of the complexes. The geochemical data can also provide meaningful conclusions about the evolving conditions of the magma source in the upper mantle beneath the stable blocks of ancient platforms.

Besides all of the theoretical aspects of these problems, they have extremely important practical impact on exploration for kimberlites, carbonatites, and numerous other mineralized complexes connected with ultramafic-alkalic and alkalic rock formations.

This study was initiated by E. Erlich and I. Zagruzina in the USSR during 1982-1983, as part of a project on the comparison of magmatic and tectonic events within the Russian and Siberian platforms. The work includes not only published radiometric data, but also a huge collection of unpublished radiometric dates from the All-Union Geological Institute of the Ministry of Geology (VSEGEI) isotope laboratory, Leningrad, USSR. More recently, the study has been continued by W. D. Hausel and W. M. Sutherland (The Geological Survey of Wyoming) and E. Erlich, who emigrated to the USA in 1984. In addition to presenting radiometric dates from ultramafic-alkalic and alkalic rocks for the Russian and Siberian platforms, we have also collected published radiometric dates on ultramafic-alkalic and alkalic rocks within the American platform.

The term "alkalic rocks" is used here in the most general sense to include rocks with high primary alkali content and alkalic rocks created as a result of redistribution of alkalies due to differentiation and metasomatism. In order to shorten the number of references, the authors refer to the latest collection of data when possible.

Temporal distribution of ultramafic-alkalic and alkalic complexes within the Russian Platform

The general distribution of alkalic and ultramafic-alkalic magmatic complexes within the Russian platform is shown on **Figure 1**. The oldest alkalic complexes within the Russian platform occur in the crystalline basement of the Baltic and Ukrainian shields. These shields are characterized by linear geosynclinal depressions separated by rigid blocks composed of Archean complexes. Complexes of alkalic rocks in the geosynclinal depressions differ in composition and genesis from those in the Archean complexes. Within mobile zones (geosynclinal depressions), the alkalic complexes are dominated by

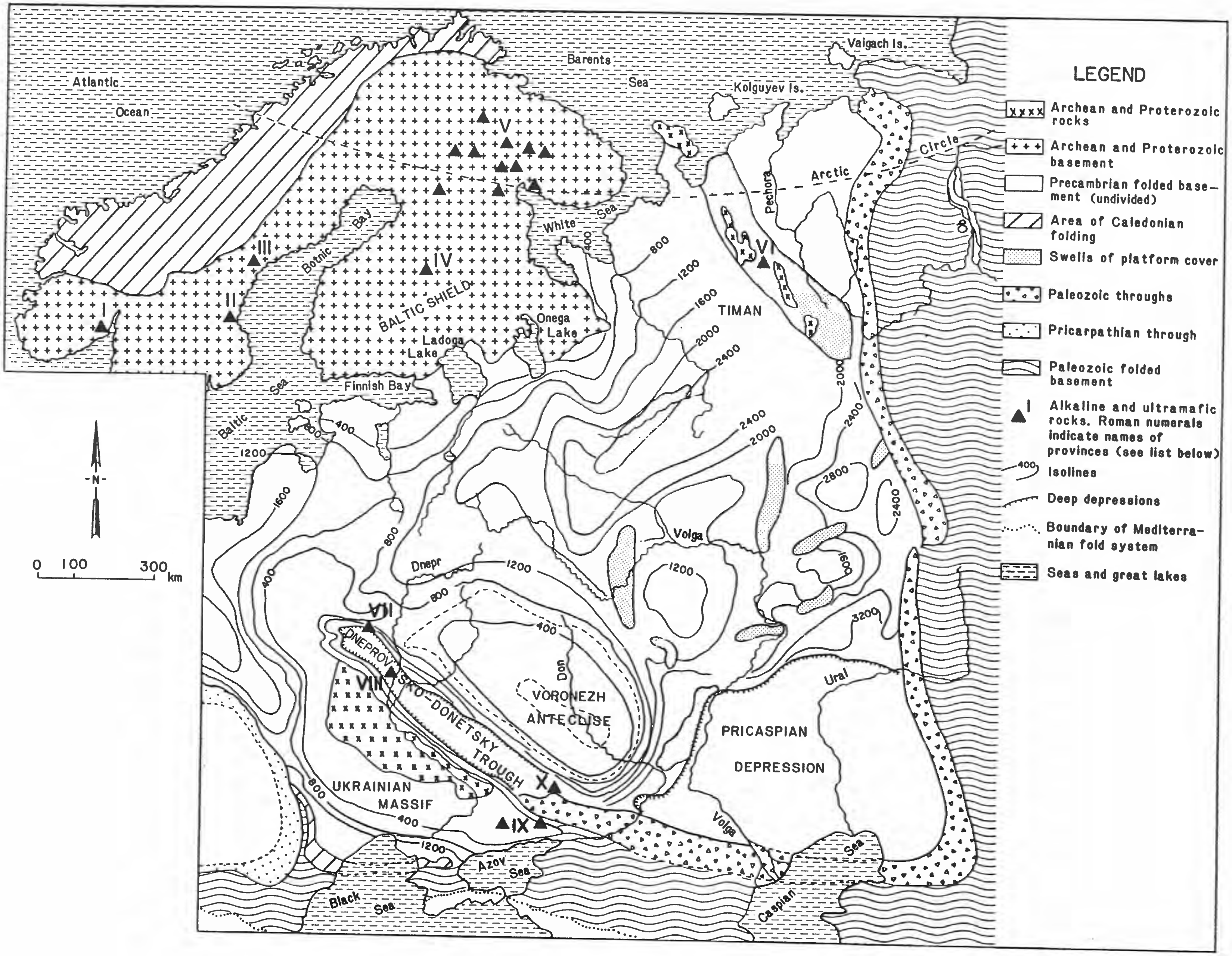

Figure 1. Spatial distribution of ultramafic-alkalic and alkalic complexes within the Russian Platform. Main regions of alkalic and ultramafic-alkalic magmatism: (I) Oslo graben; (II) Alno; (III) Almunge; (IV) Synnil'yarvi; (V) Kola Peninsula and adjacent Finland and Karelia; (VI) Timan; (VII) Prypiatsky Depression; (VIII) Chernigovsky uplift; (IX) Priazovsky region; (X) Donetsky coal basin.

alkalic granites and granosyenites; within rigid blocks, alkalic rocks are associated with massifs of mafic and ultramafic rocks.

Ukrainian shield. Alkalic rocks in the Ukranian shield are represented by the so-called Priazovsky intrusive complexes. Four such massifs have been recognized: Kal'chiksky, Kal'miussky, Elanchinsky, and Oktyaby'sky. These massifs are composed primarily of rapakivi-like granites and granosyenites, including quartz-bearing syenites. Mafic and ultramafic rocks in these massifs (except the Oktyabr'sky massif) are minor.

Twelve analyses are available for rocks of the Yuzhno-Kal'chiksky massif. A U-Pb age of monazite from an aplite pegmatite is 1,840 Ma. K-Ar ages of biotite and amphibole mineral separates are from 1,680 to 1,840 Ma without any difference in ages for the biotites and amphiboles. Two samples from amphibole-bearing granite yielded K-Ar ages of 1,690 Ma (amphibole) and 1,680 Ma (biotite). In two cases, very old ages—2,085 (amphibole) and 2,105 Ma (biotite)—were obtained.

Twenty-four age determinations are available for the rocks of the Kal'mius massif. Values obtained by the lead method for two samples of monazite from pegmatite are about 2,000 Ma. K-Ar ages of granites and syenites of the same massif range from 1,720 to 1,980 Ma. Ages obtained for amphibole and hypersthene are slightly greater than those for biotite. For K-feldspars, K-Ar ages do not exceed 1,250 Ma. The majority of K-Ar dates for the Kal'mius massif range from 1,880 Ma to 1,950 Ma. However, granosyenite intruded by malignite dikes has a younger whole-rock age of 1,600 Ma.

For the Oktyabr'sky massif, more than 60 analyses are available, including four lead dates for monazite. Most of the other dates were obtained by the K-Ar method for various minerals. Pyroxene from the most ancient pyroxenites in the massif has a K-Ar age of 2,060 Ma, and olivine from the peridotites has an age of about 2,700 Ma. K-Ar ages of phlogopite from tweitozites, which formed as the result of phlogopitization of ultramafic rocks, are 1,740 to 1,710 Ma. The same age is characteristic for mica and amphiboles from alkalic syenites in the massif. Rocks that underwent albitization (mariupolites included), sodalitization, and other late metasomatic processes, are younger. Their radiometric ages are 1,450 to 1,600 Ma. Aegirines in all of these rocks yield increased K-Ar ages that are probably due to the excess of argon. Ages of large zircon grains in mariupolites vary, but if we consider the most likely ages to be obtained by Pb-Pb ratios, their age is probably 1,730 to 1,770 Ma. Based on whole rock analyses, veins that cut the Oktiabr'sky massif date from 1,560 ±200 Ma to 1,180 Ma.

The age of the pegmatites on the Malotersiansky alkalic massif in the middle part of Dniepr River valley is about the same as the age of alkaline syenites from the Priazovsky massifs, i.e. 1,750 Ma, based on K-Ar analyses of amphiboles.

Baltic shield. The oldest alkalic rocks exposed in the Baltic Shield are Early Proterozoic. Within the geosynclinal depressions that divide the rigid Archean blocks, is the Early Proterozoic Sinnil'yarvi massif. This massif is composed of glimmerites, syenites, and carbonatites. Phlogopite from these rocks yields K-Ar ages of 1,785 to 2,030 Ma, and amphibole yields K-Ar ages of 2,260 to 2,530 Ma (Kononova and others, 1973). The Gremiakha Vyrmes, the Elet'ozero, and the Almunge formed in the Middle Proterozoic, as evidenced by K-Ar ages of 1,900 to 1,750 Ma. These massifs are all located within rigid Archean blocks reconstructed by Karelian folding. All of these massifs are composed of mafic and alkalic rocks that are associated with alkalic granites, syenites, and miaskites (Sakharyoki massif).

During formation of the platform, alkalic rock complexes tended to progress to a more uniform composition. As a rule, the ultramafic-alkalic rocks were replaced in time by peralkalic and agpaitic rocks. Magmatic bodies of these complexes are localized along lines of deep-seated fault zones. In places, these zones were rejuvenated, forming young graben systems (for example, the Oslo graben within the western part of the Baltic shield).

These structures have a tendency to rejuvenate during the later stages of their development. For example, younger-stage linear depressions tend to form locally on Ryphean aulacogens (Devonian or Carboniferous aulacogens). This style of development can be seen within the Dneprovsko-Donetsky aulacogen. During the stages of general tension and tectonic reconstruction within the platform, especially between Upper Ryphean and Vendian time, these aulacogens were partly inversed and systems of linear domes and anticlines appeared. At certain times, the aulacogens were buried under the platform sedimentary cover and became tectonically dormant, but any epoch of tension is reflected by a new stage of magmatic activity within the boundaries of the aulacogens.

Within the Kola Peninsula, alkalic and ultramafic-alkalic intrusives are arranged in three linear zones (Kukharenko and others, 1965). Such great massifs as Khibines and Lovozero are located within the peninsula, as well as a series of smaller massifs. There appear to be two different ages and intrusive compositions: (1) Caledonian, represented mainly by ultramafic-alkalic rocks, and (2) Hercinian, represented mainly by peralkalic and agpaitic intrusive complexes. Detailed isotopic studies (Kononova, 1976) show that radiometric dates, even for the single massif, embrace a time interval of about 400 Ma, and thus include the entire interval which has been considered for both complexes.

Despite the short duration of formation of several plutons (even so great as Khibines and Lovozero), radiometric dates for a series of small plutons in the same region is about in 400 Ma. It is impossible to divide intrusives into two groups combining their age and composition. Instead, one must discuss the general tendency of a single intrusive complex to evolve from ultramafic affinity during the early stages of magmatism to peralkalic and agpaitic affinity during its latter stages. This conclusion is confirmed by Rb-Sr isotopic studies for the Lovozero pluton and for a series of other massifs in the Kola Peninsula, which show the ultramafic-alkalic and alkalic rocks belong to the same single formation and have a single source (Kogarko and others, 1983; Krumm and Kogarko, 1984).

In other regions of the Baltic shield where intrusive and subvolcanic complexes of alkalic and ultramafic-alkalic rocks are present (around Oslo graben), recent radiometric studies have shown that the alkalic rocks can be divided into two episodes of magmatism: one about 600 Ma (the most ancient K-Ar dates are 665 and 675 Ma) and the second 350 to 300 Ma ago (Verschure and other, 1983). Some volcanic activity also occurred in the region around 400 to 420 Ma.

Outside the crystalline shields and within the stable platform, ultramafic-alkalic and alkalic rocks are located within aulacogens formed mainly during Late Proterozoic time (Dneprovsko-Donetsky, Pripiatsky, Viatsky, Timansky linear depressions, **Figure 1**). Within these aulacogens, ultramafic-alkalic volcanism occurs on the slopes of second-order uplifts. Thus, inside the Dneprovsko-Donetsky depression, on the slope of the Chernigovsky uplift, ultramafic-alkalic volcanics form a nearly 5,000-foot-thick sequence. Within the Pripiatsky depressions, ultramafic-alkalic massifs are located mainly on the slope of the Braginsky uplift. A small number of diatremes of ultramafic-alkalic composition are scattered throughout the stable platform. The emplacement of these diatremes was controlled by local structures. Breccia related to the diatremes was encountered in drill holes near the Arkhangelsk on the southern slope of the Voronezh anticline, within the Upper Kamsky uplift (Geochronology of the USSR, v. 2, 1974).

The most ancient phase of volcanic activity within the Dneprovsko-Donetsky aulacogen (ancient diabases within salt-dome structures) has been dated by K-Ar methods as 543 to 610 Ma Alkalic basalts and alkalic-ultramafic rocks occur at the junction between the Donetsk coal basin (Donbass) and the Priazovsky block of the Ukrainian shield. They form a 650-foot-thick sequence about 25 miles long. K-Ar ages obtained for this complex are 330 to 365 Ma. Lamprophyres within the Donetsky coal basin (Donbass) belong to three complexes: Late Permian (290 to 270 Ma), Permian-Triassic (230 Ma), and Middle Jurassic (about 160 Ma) (Geochronology of the USSR, v. 2, 1974).

The most ancient ultramafic-alkalic volcanics on the southeastern part of the Russian Platform are meimechites (K-Ar ages of 290 Ma), augitites and limburgites (382 Ma), and mica-bearing picrites (330 Ma). Nepheline syenites yield 326 Ma ages, and albitized trachytes yield 358 Ma ages. Ages of the dike swarms composed of alkalic basalts in the same region are from 358 to 240 Ma. The youngest rocks in this series are represented by monchikite dikes with ages of 162 to 163 Ma. Summarizing these data with previously published data for alkalic rocks of the Ukrainian shield (Kononova, editor, 1978) we recognize the total time for formation of this province is more than 400 Ma (see **Figure 2**).

Within the Priapiatsky linear depression, rocks of phonolite-trachyte-basalt composition form a sequence about 3,000 to 5,000 feet thick, which is

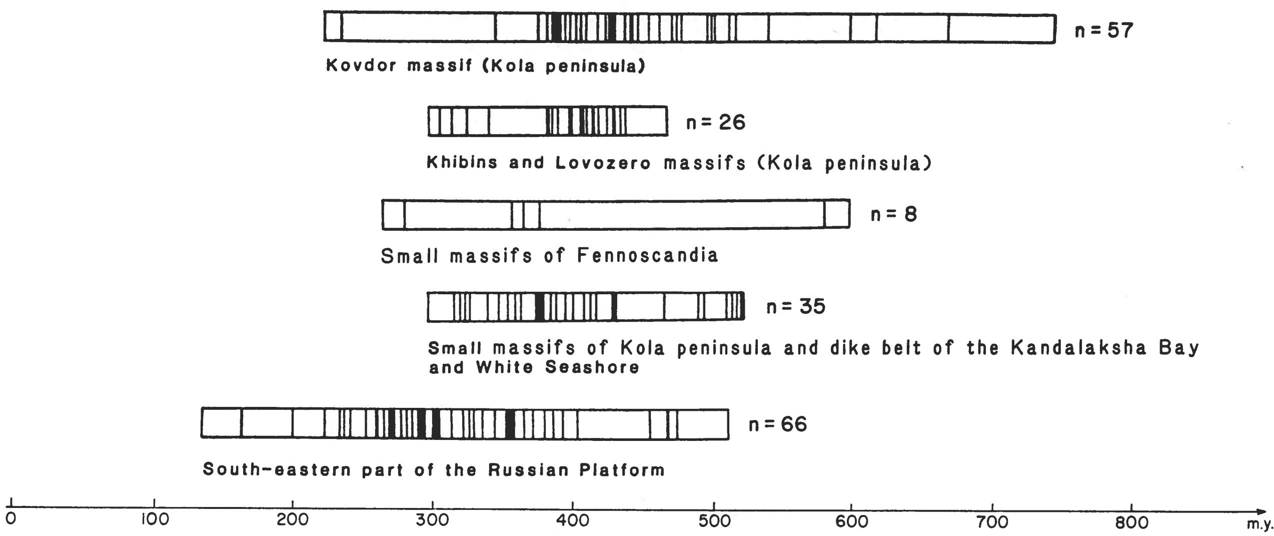

Figure 2. Duration of radiometric ages for different provinces of ultramafic-alkalic and alkalic rocks within the Russian Platform.

interlayered with sedimentary rocks of Upper Devonian age. K-Ar ages for these rocks are 354 to 358 Ma. Lamprophyres within the same structure are represented by vogesites and minnetes that are connected with the late Paleozoic-early Mesozoic activation (Korzun and Makhnach, 1977).

In the northern part of Vyatsky linear depression, volcanogenic rocks are shalshteins and tuffaceous sandstones.

The oldest carbonatite veins in the Timan region yield K-Ar ages of 680, 695, and 652 Ma (samples of Osadchuk). Alkalic gabbros from the same region yield K-Ar ages of 534, 520, and 516 Ma. Olivine diabases, camptonites, and biotite picrites, developed in the southern part of the same structure, yield K-Ar ages of 535, 546, and 545 Ma (Geochronology of the USSR, v. 2, 1974; Stepanenko, 1984). They cut Precambrian sequences and are overlapped by Middle Devonian deposits (Shutov and others,1983).

Temporal distribution of ultramafic-alkalic and alkalic complexes within the Siberian Platform

Alkalic and ultramafic-alkalic complexes within the Siberian Platform occur either in the complexes of the platform's crystalline basement or are distributed in the overlying sedimentary-volcanogenic cover (**Figure 3**).

The most ancient manifestations of different kinds of alkalic rocks within the Siberian Platform are located within the Aldan shield, where they are the part of the crystalline basement complexes. They are polychronous . Different groups of these rocks, which belong to the crystalline basement of the platform, are connected with Late Proterozoic linear depressions and are located along deep-seated faults formed or rejuvenated during middle to late Paleozoic (or even Mesozoic) time.

The oldest alkalic rocks are diopside metasomatites with economic deposits of magnetite, phlogopite, and apatite. The formation of these complexes is connected with rigid dislocations, which occurred under low temperature amphibolite facies metamorphism and were accompanied by intrusion of granite-pegmatite dikes. Isotopic data indicates the time of this diastrophism was 1,700 to 2,150 Ma. The calculated time of sphene crystallization in crystalline schists of the so-called Yengrsky series, which formed under conditions of amphibolite facies of metamorphism, is 1,975 ±65 Ma (based on U-Pb and Pb-Pb isochrons). Six determinations made on diopside from bimetasomatitic diopside-bearing rocks yielded a K-Ar age of 2,150 ±220 Ma. Diopside from metasomatic veins associated with industrial deposits of phlogopite and magnetite were dated for diopside, amphibole, and phlogopite (K-Ar) and for allanite (U-Pb). Inclination of the curve on the plot constructed from K-Ar data corresponds to an age of 1,895 ±55 Ma, which is in good accordance with the U-Pb date for allanite of 1,900 ±100 Ma (Mikhailov and

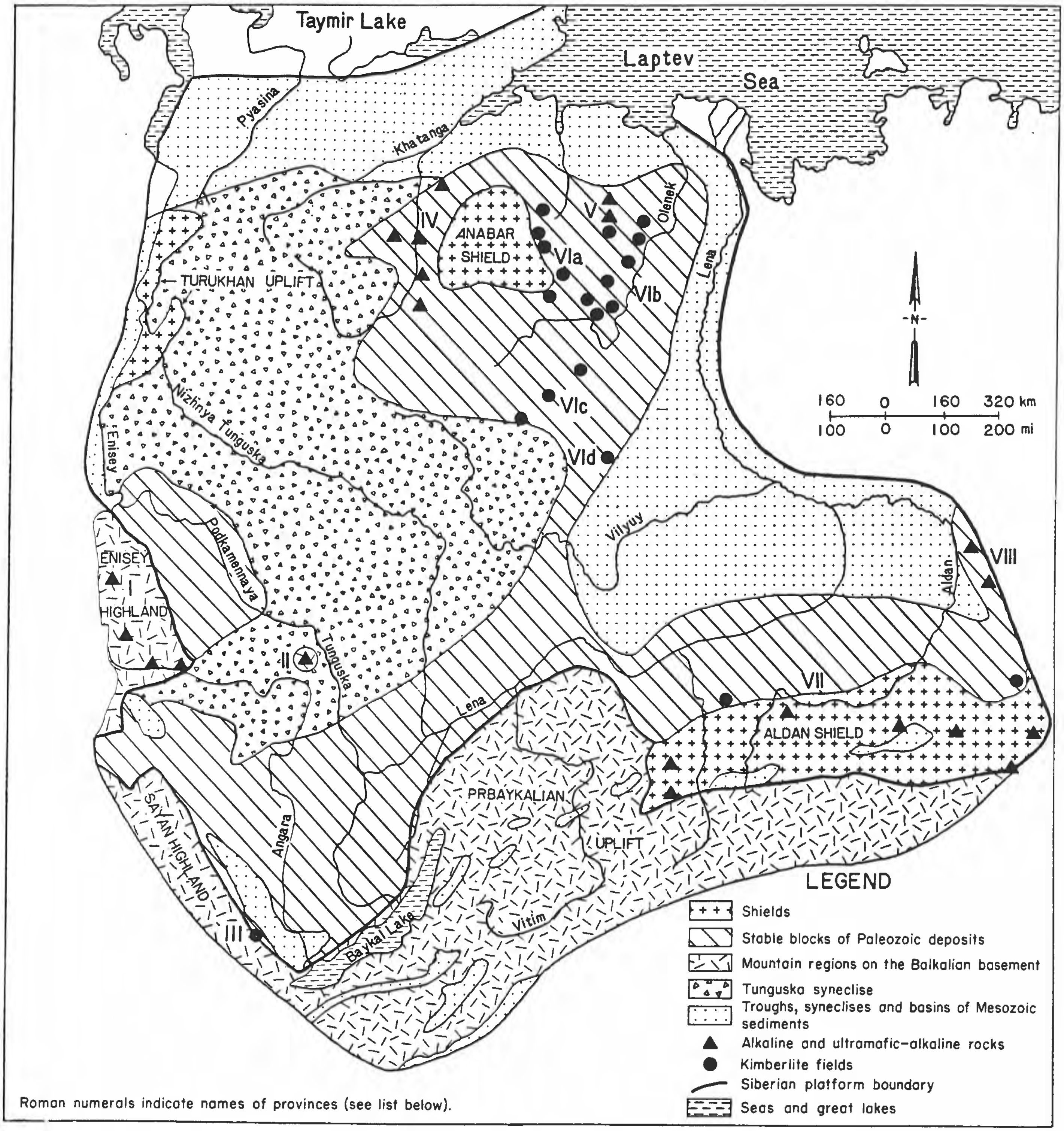

Figure 3. Spatial distribution of ultramafic-alkalic and alkalic complexes within the Siberian Platform. Main regions of alkalic and ultramafic-alkalic magmatism: (I) Enisey Highland Province; (II) Chadobetsky Uplift Province; (III) Eastern Sayan (Ziminsky) Province; (IV) Kotuy-Maimecha Province; (V) Udjinsky Province. Main regions with kimberlite fields: (VIa) Anabarsko-Djelindinsky; (VIb) Oleneksky; (VIc) Daldyn-Alakitsky and Munsky; (VId) Batuobinsky; (VII) the Aldan Shield Province of alkalic and ultramafic alkalic magmatism; and (VIII) the Stanovoy (Ingily-Arbarastaakh) Province.

Levchenkov, 1974). Blastomilonitic zones along regional faults give K-Ar whole-rock ages of 1,850 ±58 Ma and granitic pegmatites that cut these zones have K-Ar biotite and amphibole ages of 1,750 Ma and U-Pb allanite ages of 1,700 ±120 Ma.

Intrusion of Middle Proterozoic alkalic granitoids in the Aldan shield region accompanied formation of the Ulkan linear depression, which is filled with sedimentary and volcanic rocks. The upper boundary of the Ulkan granites is transgressively overlapped by deposits of the Upper Proterozoic Inninsky suite. Three intrusive phases: syenites, biotite granites, and alkalic granites have been identified within this intrusive complex. Their radiometric ages (based on K-Ar data) range from 1,600 to 1,770 Ma (Kazakov and Knorre, 1973). A complex of middle Late Proterozoic intrusions, composed of ultramafic-alkalic rocks associated with alkalic rocks and carbonatites, are located in the eastern and southeastern parts of the shield. The Konder, Arbarastakh, Ingily, Chad, and Inagly massifs are associated with these Late Proterozoic intrusives. The oldest K-Ar dates for all these massifs (obtained from different minerals) are from 725 to 610 Ma (El'yanov and Moralev, 1972; Geochronology of the USSR, v I, 1973). K-Ar dates obtained for the Ingily massif by the Isotope laboratory of the All-Union Geological Institute are from 85 to 115 Ma (see **Figure 4**).

The Udja Province of ultramafic-alkalic rocks, located east of the Anabar shield, is correlated with the Udja anticline, formed during a tectonic reconstruction epoch between Late Ryphean and Vendian time (600-700 Ma) as a result of inversion of the Ryphean aulacogen of the same name. The oldest ultramafic-alkalic rocks are about 720 Ma, followed by a series of intrusive phases with K-Ar ages of 400 to 420 Ma and 320 to 340 Ma. The last phase of magmatic activity is dated about 250 Ma (Erlich and Zagruzina, 1981).

The structural position of the Maimecha-Kotuy ultramafic-alkaline province west of the Anabar shield, is also controlled by the Ryphean north-south elongated aulacogen (Erlich, 1985). In contrast to the adjacent Udja Province of ultramafic-alkalic rocks, it shows a comparatively narrow interval of radiometric ages of 248 to 264 Ma for small massifs and 220 to 245 Ma for the great Guli massif (Prokhorova and others, 1966; Bagdasarov and others, 1983). For this province, a similar relationship occurs for Khibines and Lovozero plutons within the Kola peninsula, i.e. there are some geological indications that ultramafic-alkalic massifs of Ryphean age (in any case Precambrian), and probably also Jurassic age, can be found.

Geological data indicates that kimberlites from the fields located east and southeast of the Anabar shield were formed in several phases. The oldest phase of kimberlitic volcanism occurred after Ryphean and before Vendian time. Fresh and coarse grains of pyrope, chrome-diopside, and picroilmenite occur in gravels of the Vendian Tomtor suite within the Udja anticline. Other stages of kimberlitic volcanism have occured in the Late Devonian-Early Carboniferous, and Permian-Triassic. Additional stages are dated less accurately as pre-Early Jurassic, pre-Late Jurassic, pre-Valanzhinian and pre-

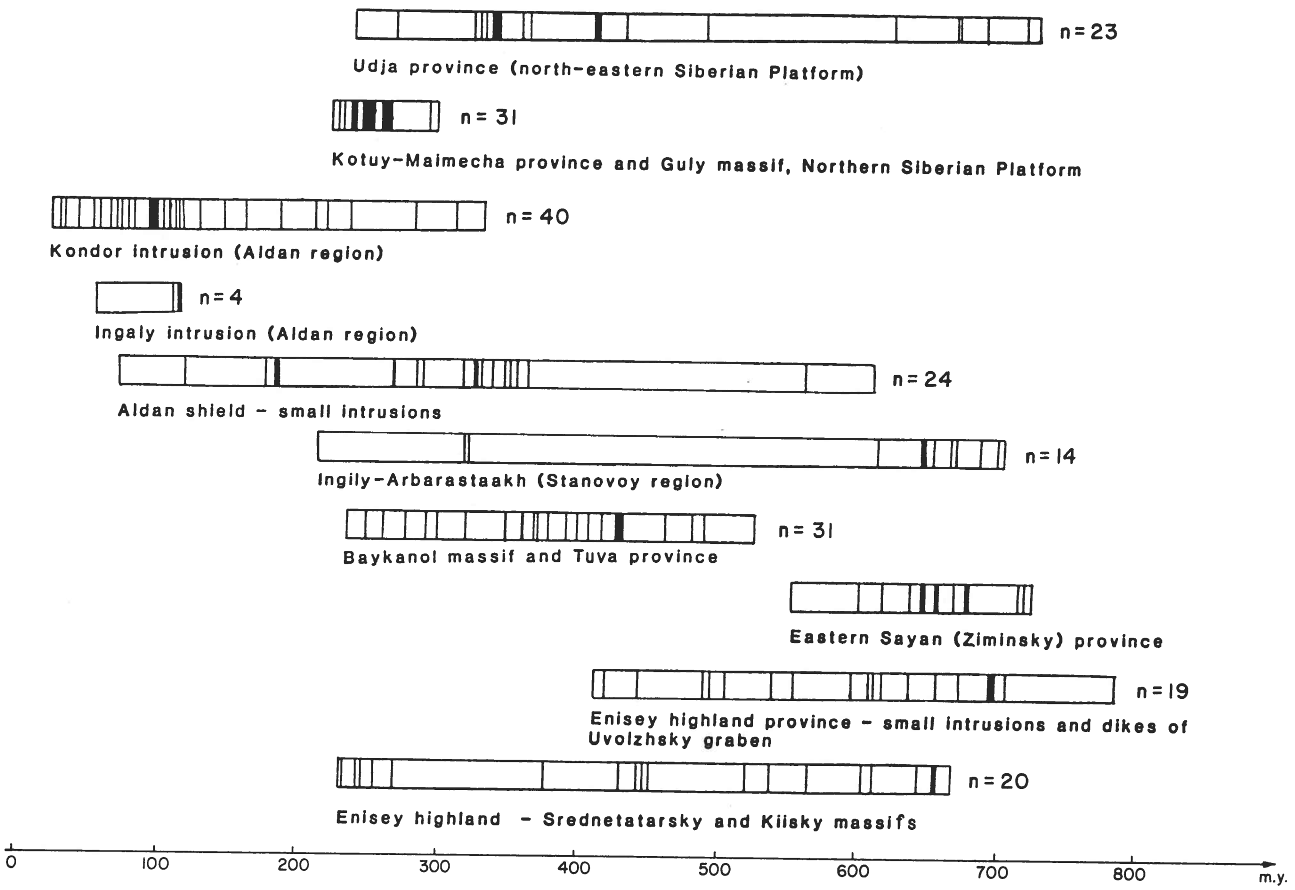

Figure 4. Duration of radiometric ages for different provinces of ultramafic-alkalic and alkalic rocks within the Siberian Platform.

Late Cretaceous. There are also fresh grains of coarse pyrope, chrome-diopside, and picroilmenite in terrigenous fragmental rocks developed along the Permian-Mesozoic Leno-Anabar trough's southern boundary. Radiometric data available for kimberlites (**Figure 5**) suggests kimberlite volcanism had the same total duration of about 400 Ma. This duration is equivalent to that of the ultramafic-alkalic rocks of Udja Province.

Mesozoic ultramafic-alkalic and alkalic rocks located within 10 different regions in the eastern part of the Aldan shield are localized along fault zones generated during Mesozoic tectono-magmatic activation. The Central Aldan region is the best studied (Kravchenko and Vlasova, 1962). The oldest radiometric dates in the Central Aldan region have been determined for zircons from alkalic granites of the Nygvagimsky massif, located in the southeastern part of the shield. By different isotopic ratios, the rocks of the massif range from 190 Ma to 380 Ma. The least meaningful of these radiometric ages was determined for alkalic basaltic rocks of the Tommot massif (110 Ma). K-Ar ages for different rocks in the same region are 165, 195, and 180 Ma. Total duration of this type of volcanism is similar to those determined for the Baltic shield and the Udja Province. The times of certain phases of volcanism in all these regions also coincide (**Figure 4**).

Small dikes of ultramafic-alkaline rocks are also located in the southwestern part of the Siberian platform within the so-called Chadobetsky uplift. Here, as in the Maimecha-Kotuy province, it seems from the data now available that ultramafic-alkalic magmatism occurred during one comparatively short phase.

Distribution of ultramafic-alkalic and alkalic complexes within the North American Platform

The general distribution of alkalic and ultramafic-alkalic complexes within North America is shown in **Figure 6.** These complexes are separated into seven provinces: (1) shield; (2) Labrador; (3) Ottawa-St. Lawrence-Grenville; (4) Appalachia (5) Ouachita; (6) Cordillera; and (7) Innuit.

These provinces are roughly similar to the Precambrian terranes of King (1977) and Gibbs (1956), with some generalizations taken from Currie (1976) and a variety of other sources. A collection of published radiometric dates of alkalic rocks in North America was initially compiled by Karl G. Albert and W. Dan Hausel of the Geological Survey of Wyoming. Subsequently, all data were compared with a catalogue of data recently published by Woolley (1987).

Alkalic magmatic massifs and volcanic centers appear to be controlled by deep-seated structures or zones of weakness. Provinces described here overlap in some areas, with younger magmatism intruding older terranes. In the southwestern part of the Cordillera Province, sporadic alkaline magmatism occured in what was the western continental margin of North America during

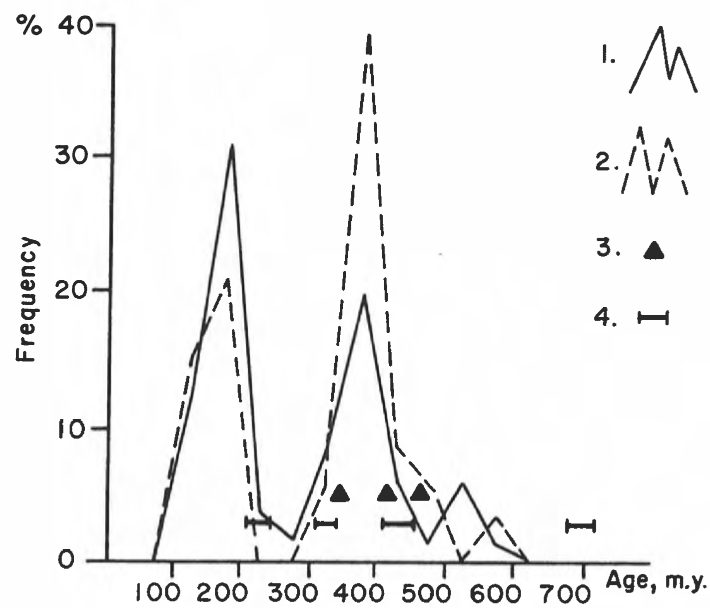

Figure 5. Age of kimberlitic complexes within the Siberian Platform (from Erlich, 1985). (1) Histogram of kimberlite radiometric age data of Lower Olenek groups of fields. Age determined by K-Ar method, Pb206/U238 ratio, and by fission track. Data from Brakhfogel and others (1980). (2) Histogram of kimberlite age radiological data for different groups of fields determined by fission-track method. Data from Komarov and Ilupin (1975). (3) Radiological dates for kimberlites of Malo-Baloubiya and Daldyn-Alakit region, mainly by K-Ar method. Data from Brakhfogel and others (1980). (4) K-Ar data for minerals from Tomtor ultrabasic-alkaline massif. Data from Erich and Zagruzina (1910).

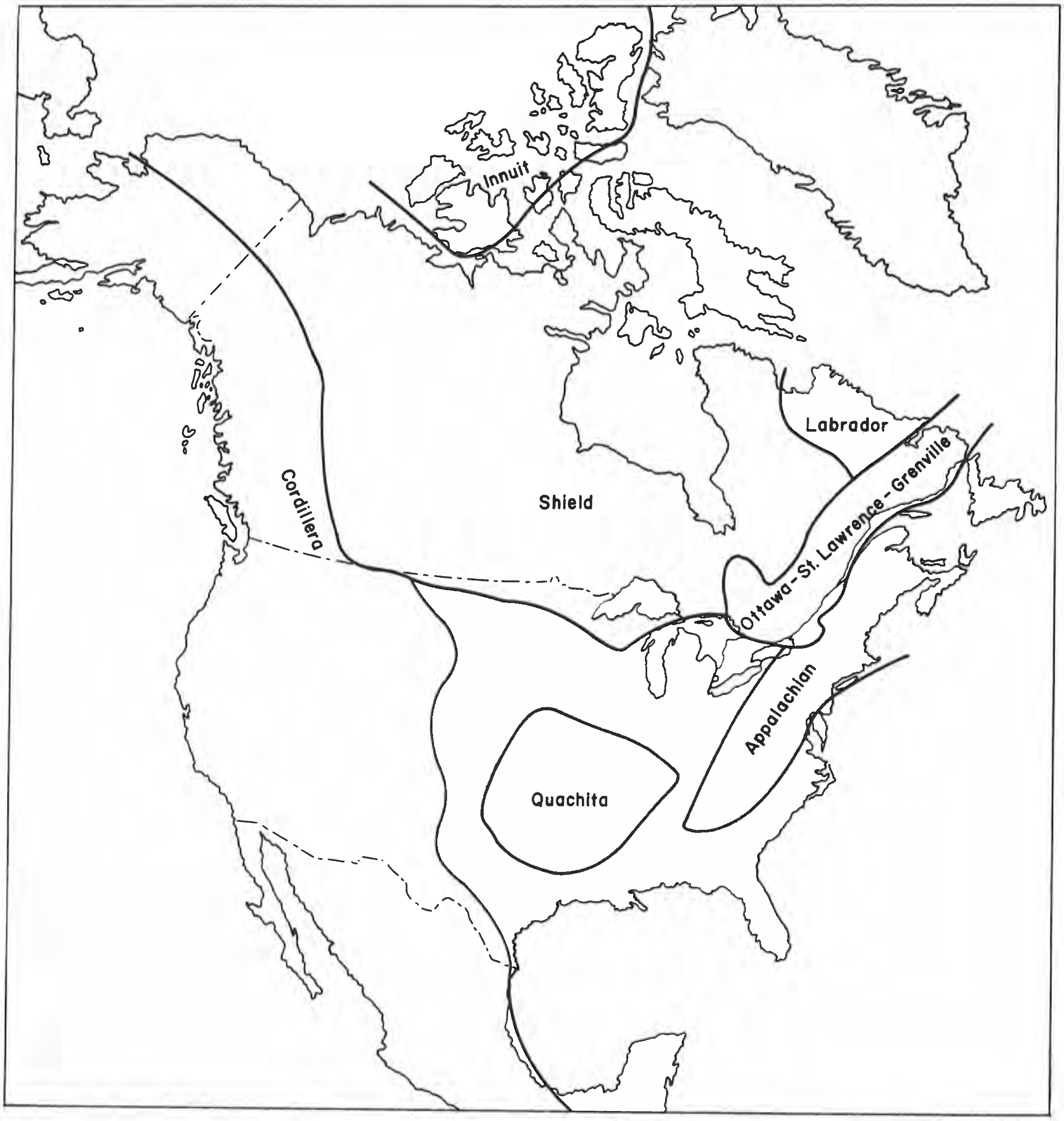

Figure 6. Spatial distribution of ultramafic-alkalic and alkalic provinces within the North American Platform.

late Precambrian time. Partial discussions of continental geography and tectonics at that time can be found in Profett (1979) and Burchfiel (1979). After about middle Paleozoic time, the Cordillera became a dominant influence, which disrupted the earlier Precambrian continental margin.

Figure 7 shows alkalic rock provinces and ages of specific occurrences of alkalic rocks. These are grouped into seven apparent pulses of alkalic magmatism within North America. Each data point (or vertical bar) in the diagram represents the age of one rock occurrence. Where more than one date is given for an occurrence, the average of those dates was used unless the reference sources gave reasons why one date may be more reliable than others. At sites where more than one occurrence has been dated, all ages are addressed as separate data points. Where relative geologic ages are given rather than radiometric ages, an approximate age has been assigned. Age groupings were first visually identified and then examined for possible geologic causes.

1. The Shield Province includes practically the entire Canadian Shield and is composed of Precambrian terranes of different ages. Most alkalic intrusions in the province are described as carbonatites, although the northwestern Quebec dikes are lamprophyres [K-Ar ages on phlogopite of 1,010-1,520 Ma (Currie, 1976)]. Two other localities in the province are described as kimberlites. Overall, the ages for the Shield Province alkalic igneous rocks range from 867 to 2,706 Ma.

These ages represent several separate pulses of alkalic magmatism on the North America continent. A large part of the alkalic magmatism in the Shield Province is synchronous with Middle Proterozoic (Grenvillian) magmatic bodies intruded further to the southeast along the continental margin.

The oldest alkalic magmatic pulse in the Shield Province is about 2,700 Ma. This pulse includes a group of dates for the syenite pyroxenite intrusion near Poobah Lake, K-Ar isochron age of 2706 ±46 Ma (Woolley, 1987), and a Rb-Sr isochron age for rocks of the Kaminak Lake massif of 2,686 Ma (Currie, 1976). However, a K-Ar age of biotite from the same massif was 1,820 ±60 Ma. Close to these are K-Ar dates 2,170 and 2,200 Ma for ultramafic rocks to basanites of the Easter Island dike (Woolley, 1987). Similar ages (2,057-2,166 Ma) were obtained by K-Ar method and Rb-Sr isochron for syenites and peralkaline granites of the Blachford Lake massif (Woolley, 1987).

The second group of dates includes K-Ar dates on biotite from almost identical carbonatites and pyroxenites, intrusions at Argor and Goldray, Ontario. Both show similar aeromagnetic anomalies. They date 1,655 and 1,695 Ma, respectively. A similar K-Ar age (1,740 Ma.) was deteremined for another pyroxenite-carbonatite complex at Cargill, Ontario. This alkalic magmatism corresponds to the time of the Hudsonian orogeny. Nepheline syenite and syenite complexes at Wausau and Stettin, Wisconsin, gave Rb-Sr ages of 1,436, 1,446, and 1,507 Ma, and appear to be Elsonian activity between the Hudsonian and Grenvillian pulses.

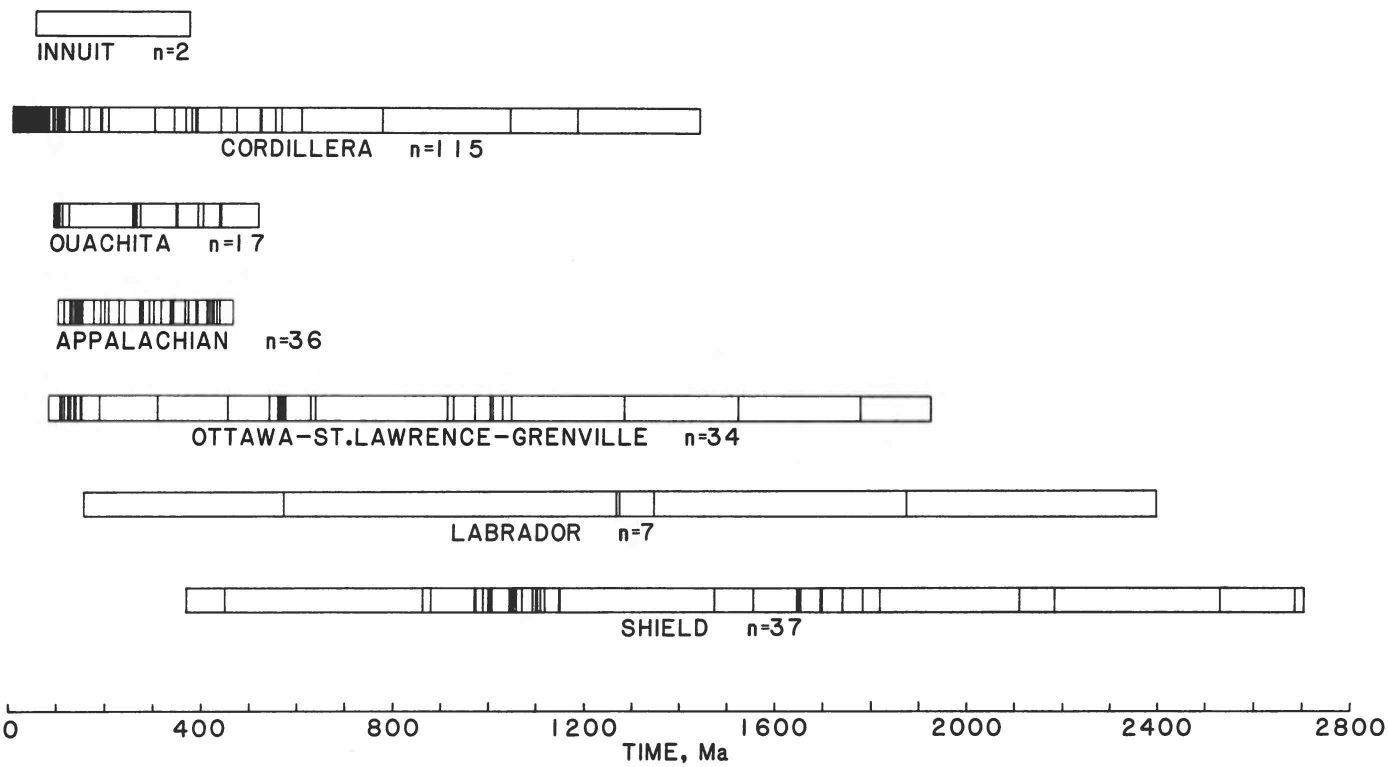

Figure 7. Duration of radiomeric ages for different provinces of ultramafic-alkalic and alkalic provinces of North America.

The third group of dates ranges from 870 to 1,185 Ma. Considering possible analytical error, its time can be determined as 1,000 ± 50 Ma, which corresponds well with the time of the Grenville episode of tectonic activity. This episode includes dates on carbonatitic massifs at Big Beaver House (1,005 Ma by K-Ar method); Prairie Lake (1,112 by K-Ar and 1,023 ±74 Ma by Rb-Sr isochron); Teatzel Township, Ontario (K-Ar date for phlogopite 1,155 Ma); Coldwell, Ontario (1,044 ±6.2 Ma by Rb-Sr isochron based on 17 rocks); Killala Lake oval complex of fenitized rocks (1,185 ±90 Ma by K-Ar on biotite from gabbro and 1,050 ±35 Ma by Rb-Sr whole rock isochron); and nepheline syenite-ijolite complexes at Nemegosenda Lake, Seabrook Lake, and Lackner Lake, Ontario (K-Ar and Rb-Sr analyses ranging from 1,010 to 1,138 Ma). Kimberlite at Bachelor Lake, Ontario yielded a phlogopite K-Ar age of 1,100 Ma (Watson, 1967).

Paleozoic alkalic magmatism within the Shield Province is practically absent. Geologic relationships indicate that the kimberlite at Coral Rapids, Ontario, is post-Middle Devonian (Dawson, 1980; and Currie, 1976). Rb-Sr data were obtained for the Hecla-Kilmer complex, Ontario, but they did not define an isochron. A least-squares fit through the data points indicated an age of 450 Ma, but this was not considered reliable (Woolley, 1987).

2. The Labrador Province covers the area northeast of the Shield Province and north of the Ottawa-St. Lawrence-Grenville Province. The most ancient dates of alkalic rocks within the province (2,398 ±72 Ma) are associated with the Goodwood River plutons of nepheline syenites. The next stage of alkalic magmatism took place around 1,873 Ma, when carbonatites of the Castignon Lake formed. Around 1,200 to 1,300 Ma, peralkalic granites of Strange Lake and Flowers Bay and a significant part of the Red Wine pluton formed. Alkalic magmatism occurred around 570 Ma, as shown by carbonatites at Allik, with a K-Ar date on biotite (Currie, 1976).

3. The Ottawa-St. Lawrence-Grenville Province stretches along the southeastern edge of the Shield and Labrador Provinces. Radiometric data cited below for this province comes from Woolley (1987). The most ancient radiometric dates for alkalic rocks within the province are whole-rock Rb-Sr analyses for syenites of the Otto Stock (1,700-2,150 Ma), and the Nemag Lake fenites (considered to have formed between 1,700 and 2,150 Ma). Numerous radiometric dates are concentrated within the time between 1,220 and 900 Ma. These include the nepheline syenites of Blue Mountain (Rb-Sr whole-rock age of 1,285 ±41 Ma), NW Quebec dikes (K-Ar ages of 1,110-1,520 Ma), and the Deloro Stock (Rb-Sr isochron ages of 1,096 ±48 Ma and 1,059 ±46 Ma, and K-Ar age of riebeikite of 875 Ma). Dates for nepheline and biotite from pegmatites of nepheline gneisses of the Monmouth and Glamorgan Townships, Ontario, are 8,58 to 1,003 Ma. U-Pb age of nepheline syenites of the French River massif is 975 Ma. A minimum age of 1,050 Ma is considered for the carbonatites of Sullivan Island, Ontario. All radiometric dates from the rocks of the ultramafic-alkalic ring of pluton Ste. Veronique fall within the interval 889-1,226 Ma. The time interval encompassing the Ste. Veronique, the Deloro Stock, and NW

Quebec dikes is about 400 Ma. It can be considered as a single eruptive event. Dates of about 900 Ma are considered in many of these cases to reflect a metamorphic event, as confirmed by radiometric ages for metamorphism on nepheline gneisses of York River, Ontario. However, a similar radiometric age is also characteristic of magmatic rocks such as the Meach Lake carbonatites.

The next stage of intensive magmatic activity took place around 560 to 580 Ma, when a series of magmatic bodies near Nippissing Lake, Ontario formed (K-Ar date of 560 Ma for biotite separated from carbonate-rich syenite fenite on Manitou Island; K-Ar ages of 568 and 575 Ma on biotite from lamprophyre and nepheline syenite of the Callendar Bay complex). The same age has been determined for carbonatized kimberlites from Arvida (K-Ar whole-rock date of 568 Ma and biotite dates of 560 and 563 Ma).

The youngest alkalic activity within the Province occurred around 85 to 141 Ma. This age is characteristic of numerous Monteregian intrusions. Activity within this time is represented essentially by alkalic metasomatism. K-Ar dates from the Oka massif range from 95 ±5 to 114 ±7 Ma, with a K-Ar isochron based on 28 determinations from seven units at 117 Ma. A Rb-Sr whole-rock isochron for the Mt. Johnson massif is dated at 111 ±6 Ma, with K-Ar dates of 117 ±9 Ma and 120 ±8 Ma.

4. The Appalachian Province parallels the southeastern edge of the Ottawa-St. Lawrence-Grenville Province, extending from the Appalachian belt to New Brunswick and Newfoundland with the same prevailing type of alkalic volcanism as that found in the Ottawa-St.Lawrence-Grenville Province. The most typical intrusive rocks are peralkaline granites and a variety of syenites. These rocks represent an extreme end of a rock series from gabbro to monzonites, riebekite granites, and syenites. These rocks usually form comparatively small intrusive or subvolcanic bodies, but at least in one case, the White Mountain magma series, they formed a batholith with associated volcanic and dike complexes and a series of small intrusive bodies of corresponding composition, which included foyaites, essexites, and kimberlites.

The most ancient radiometric dates known within this Province are close to 450 Ma (458 Ma for the Quincy granites, 437 for the Gulf of Maine granites). Ages of about 300 Ma are characteristic of peralkalic syenites of the La Scie complex (Woolley, 1987). Monchiquites of Notre Dame Bay have K-Ar ages of about 140 Ma. The youngest dates are around 100 Ma (96.4 and 100 ±2, from Cuttingsville, Vermont). Intermediate stages of magmatic activity took place around 200 Ma (194-198 Ma at Red Hill, New Hampshire), 240 Ma (227-228 Ma at Agamenticus, New Hampshire; 233-234 Ma and 242-245 Ma at Litchfield, Maine), and 350 Ma (365 Ma for the Quincy granites, Massachusetts; 350 and 367 Ma for the Peabody granite-syenites, Massachusetts). The total duration of alkalic magmatism within the Appalachian Province exceeds 350 million years. Radiometric dates within a single magmatic complex may vary, as in the Quincy granites, which range from 458 ±14 Ma to 282 ±8 Ma, and in the White Mountain magma series, which ranges from 226 Ma to 110 Ma.

5. The Ouachita Province in the southern midcontinent experienced alkalic magmatism at about the same time and of similar composition to that found in the Appalachian Province. The age of alkalic magmatism in the Ouachita Province shifts noticeably southwestward from Paleozoic to Mesozoic. The most ancient radiometric dates range from 495 to 525 Ma (Reformatory and Quanah Granites, Oklahoma). More than 79 small diatremes and dikes near Avon, Missouri have radiometric ages of 377 to 399 Ma. Dikes and sills of mica peridotite near Hicks Dome, Illinois, gave K-Ar ages of 252 ±13 and 269 ±13 Ma (Woolley, 1987). The most common dates within this Province are grouped around 100 Ma (ijolites and melateigites from Magnet Cove, Arkansas; lamproites from Woodson County, Kansas and Prairie Creek, Arkansas; and pulaskites from Little Rock, Arkansas and Granite Mountain, Arkansas). The youngest radiometric date available for the Province is 79 ±2.9 Ma, obtained for phonolite from the borehole within Monroe uplift, Mississippi (Woolley, 1987). The total range of radiometric ages available for this province is about 430 million years.

6. The Cordillera Province embraces practically the entire Rocky Mountains area. For structural reasons, this province is usually divided into several subprovinces: Alaska, Canadian Cordillera, Montana, Cascades, Basin and Range, and Mexican Cordillera.

Precambrian and Paleozoic magmatic bodies are located mainly within the southwestern part of the Cordillera Province (California, Colorado, New Mexico). They are distributed mainly along lines of deep-seated fault zones developed along the boundaries between different type of Precambrian sequences or along the Precambrian margins of North America.

The most ancient radiometric dates (1,523-1,380 Ma) were obtained for the alkalic complex of Mountain Pass, California, which includes alkalic granites, shonkinites, and syenites with associated carbonatites. The second stage of alkalic magmatic activity within the province took place around 1,040 to 1,190 Ma, with the emplacment of Pajarito Mountain, New Mexico carbonatites and the alkalic material associated with the Mount Rosa, Colorado granites. During the Avalonian epoch, carbonatites of Mt. Grace, British Columbia were emplaced at 773 Ma (Hoy and Kwong, 1986). The Lobo Hill syenite, New Mexico, intruded Precambrian schists about 604 Ma.

An extensive epoch of carbonatitic volcanism took place around 506 to 570 Ma. It includes Iron Hill (550-570 Ma), McClure Mountain (506-535 Ma), Democrat Creek (511-534 Ma), and Gem Park, Colorado (551 Ma). The youngest Paleozoic date is a Rb-Sr isochron dating of a syenite dike from Pedernal Hill, New Mexico (469 ±7 Ma). The same stage of alkalic volcanism probably included a melteigite dike in the Monte Largo Hills near Albuquerque and carbonatite dikes exposed within the Lemitar Mountains, New Mexico. The oldest (406 ±16 Ma) K-Ar date obtained for hornblende from the syenitic massif of Chichagoff Island, Alaska, belongs to the same stage of activity. Clasts of syenite are found in Silurian and Devonian sedimentary rocks, indicating that the complex is Silurian or older (Woolley, 1987).

The next epoch of intensive alkalic magmatism within the Cordillera took place around 250 Ma. During this stage, syenites and carbonatites of the Ice River massif were formed. K-Ar dates vary from 220 to 392 Ma, whole rock Rb-Sr isochron ages vary from 244 to 280 Ma, and a reliable Pb-U zircon age of 320 ±4 Ma is cited by Woolley (1987). The next pulse of alkaline magmatic activity took place around 180 Ma, when the Cariboo Bell Laccolith (1847 Ma), Kamloops syenites (about 200 Ma), and the syenite-pyroxenite complex of Kruger Mountain (170.9 ± 5.1 Ma and 152 ± 9 Ma) were formed.

The most intensive epoch of alkalic volcanism in the Cordillera Province occurred around 100 Ma. Most of the radiometric dates obtained for the Alaskan Subprovince are from this epoch: 107 ±3 Ma for the Hunt Complex, 106 ±3 Ma for Granite Mountain, and 105 ± 3 Ma for the Dry Canyon Stock. Alkalic magmatism was also very common during this time in the Canadian Cordillera. In particular, the Crowsnest volcanic series of trachytic analcime-bearing agglomerates: tuffs and lavas were formed around 100 Ma (Curry, 1976), and a similar age (80 ±13 and 91 ±5 Ma) was reported by Woolley (1987) for the syenitic intrusion of the Tombstone batholith. The Cascade subprovince contains alkalic volcanic rocks as old as 100 Ma in nothernmost Washington, on the boundary with the Canadian Cordillera (syenite-malignitic complex of the Similkameen pluton, with K-Ar ages of 70 and 83 Ma for biotite and 105, 155, and 177 Ma for hornblende). Some similar K-Ar dates were obtained from the rocks of the Montana Subprovince. Significant alkalic magmatic activity also took place in the Canadian Cordillera around 50 Ma, with formation of the nephelinites of Ting Creek (53.1 Ma); syenomonzonites of Goosly Lake (48.8 ± 3 Ma); the Marron complex and the Coryell intrusion (48-58 Ma), and magmatic rocks of the Sweet Grass Hills, Alberta (48 Ma). The Mount Copeland lamprophyres and syenites within nepheline gneisses (48 Ma) may reflect metamorphism rather than magmatism. The same time interval includes the youngest radiometric date from Kruger Mountain (69.1 Ma for biotite from shonkinite), giving a time interval of formation for this massif of about 100 million years.

Alkalic and ultramafic-alkalic rocks of the Montana Subprovince syenites, alnoites, latites, and phonolites have K-Ar ages from 49 to 94 Ma. This may reflect previously mentioned pulses of magmatic activity that occurred about 100 and 50 Ma.

During the last 40 million years, pulses of intense alkalic magmatic activity occurred around 35 Ma (Trans-Pecos Texas Province); 30 Ma (kimberlites of Arizona, New Mexico, and Colorado; alnoites of Smoky Butte, Black Hills, South Dakota; and alkalic silicic volcanism of the Sierra Madre Occidental); 6 to 9 Ma (alkalic silicic magmatism in the Cascades); and 1.5 Ma (the Leucite Hills, Wyoming; alkaline basaltic fields in Pribiloff Islands, Mexico; and the silicic alkaline complexes of Canada). Study of the distribution of alkalic magmatic activity in the Northern Circum-Pacific for this time (Erlich, in press) shows that types of volcanic activity vary depending on structural conditions: eruptions of alkalic basalts in one type of region corresponds to increased eruptions of subalkalic silicic explosive volcanism in regions of another type.

7. The Innuit Province is poorly studied but the available information implies some alkalic magmatism over the period of 47 Ma to about 400 Ma. Quartz monzonites from the Cape Richards intrusion are dated at 347 to 390 ±18 Ma, and nephelinite and phonolite dikes, plugs, diatremes, and sills of Freeman Cove are dated
at 47 ±4 Ma.

Analysis and conclusions

There appears to have been several synchronous pulses of alkalic magmatism that coincide with tectonic events (Hausel and others, 1989):

A. The most ancient radiometric dates obtained for alkalic rocks—about 2,700 Ma—coincide with the earliest stages of metamorphism that affected the most ancient rocks on the Russian, Siberian, and North American platforms.

B. The last orogenic episode before platform stabilization involved the emplacement of a large number of granitic intrusions along with folding (Karelian folding within the Baltic shield and the Hudsonian orogenic event in North America). It also involved the rejuvenation of radiometric ages of metamorphic rocks (so-called Svecofenian regeneration within the Baltic shield) at about 1,950 to 2,100 Ma.

C. The time of platform stabilization within all three platforms—Russian, Siberian, and North American—was marked by emplacement of rapakivi-type granitic intrusions about 1,750 ±100 Ma.

D. Tectonic reconstruction at the end of Ryphean time (the termination of the development of the Ryphean aulacogens and the formation in their place of a series of linear anticlines) occurred at about 720 to 750 Ma.

E. The early Caledonian stages of tectonic reconstruction of the ancient platforms took place 550 to 561 Ma and 420 to 440 Ma.

F. Other stages of tectonic reconstruction of platforms occurred 320 to 340 Ma, around 250 Ma, 160 to 180 Ma, and 100 Ma.

G. The most recent stages of alkalic magmatic activity occurred about 35 Ma, 30 Ma, 6 to 9 Ma, and 1.5 Ma.

Similar data exists for the carbonatite provinces in the Northern Territory of Australia (Black and Gulson, 1978) and in Western Africa (Liegolis and others, 1983).

Data on the temporal distribution of alkalic volcanism during the last 40 million years indicates that the real duration of the synchronous pulses of alkalic volcanism are very short (about 4 Ma.). Even shorter pulses (around 1 Ma) can be suggested. The time of the suggested pulses is the same within different plates, but the character of magmatic activity during each pulse is different within different blocks. The synchrommouse events are characterized in some regions by intensive alkalic magmatism and in other regions by intensive subalkalic silicic explosive volcanism and emplacement of granitoid intrusions, i.e. these two kinds of volcanic activity, which reflect vations in volatile content/pressure, can replace each other in different geodynamic conditions (Erlich, in press).

It is possible to mark the coincidence of the beginning of the earliest alkalic magmatism in such provinces as the Kola peninsula and Oslo graben (Russian Platform), and the Udja province and the Ziminsky and Ingily-Arbarastaakh regions (Siberian Platform). Similar stages of alkalic activity have been described above for North America. The coincidence of timing of the suggested pulses within the three major ancient platforms of the Northern hemisphere shows that these pulses are not limited by plate boundaries. They are truly global in scale and probably reflect causal events at great depth—possibly at the mantle-core boundary.

The timing of the suggested pulses is almost universal although their intensity and character vary in different regions depending on local structural conditions. For example, there is a tendency for spreading of alkalic volcanism in time outward from the center of the American Continent toward the continental margins.

It seems that the suggested pulses coincide with epochs of global tectonic reconstruction and major stratigraphic boundaries. This will probably become even more obvious if the radiometric dates for alkalic rocks are separated into rocks that exhibit chemical affinities with primary magma from depth and those which are associated with alkalic metasomatism and other processes of alkali redistribution within a magma chamber or volcanic column.

Previously, Doig (1970) noted the similarity in age of early Paleozoic alkalic magmatism on both sides of the Atlantic Ocean floor. He thought that this similarity reflected stages of opening of the Atlantic Ocean. But if we consider the comparable stages of magmatism in Siberia it will become obvious this similarity is not related to the openings of any ocean, but rather to global pulses of another nature, such as pulsative regimes of the Earth's volatiles/heat flow. This idea is in some respect similar to the ideas of Milanovsky and Mal'kov (1980).

Within ancient platforms, the synchroneity of basaltic volcanism is different than that of alkalic magmatism. The main stage of basaltic magmatism within the Siberian platform occurred in Permian-Triassic time (about 220-260 Ma); however, there are no similar basaltic volcanic events within the Russian and

American Platforms during that time. During the same period, manifestations of kimberlitic magmatism (ultramafic-alkalic and alkalic) occurred synchronously within the North American and Siberian platforms. Widespread dates for alkalic magmatism centering around 100 Ma have been obtained in the Appalachian, Cordillera, and Ouachita Provinces and are also characteristic of the Circum-Pacific belt. Similar dates are absent in the Russian Platform. Dates for alkalic magmatism centering around 250 Ma are common in the Siberian Platform and surrounding mountain ridges as well as in the Appalachian and Ouachita Provinces, but are rare within the Russian Platform.

These differences in the degree of synchroneity can be explained by the different depths of generation of both types of magmas. All available petrological data for kimberlitic or ultramafic-alkalic magmatism supports the idea that these magmas were derived from much greater depths in the mantle than typical basalts. The greater depths of origin, combined with the synchroneity of magmatism, suggests an interrelated or global phenomenon.

The synchroneity of ultramafic-alkaline magmatism can explain the enrichment of certain elements (notably palladium) in some sedimentary sequences. The nature and importance of such an enrichment has been widely discussed in the geological literature (Alvarez, 1986, Officer and Grieve, 1986). It is interesting to note that the supporters of meteoritic impact for such an enrichment refer to the low palladium content in the products of both basaltic and silicic volcanism, but do not mention or consider the possibility of global pulses of ultramafic volcanism—the only type of magmatic event that could provide such enrichment.

The available data also provides information on the duration of alkalic and ultramafic-alkalic magmatism. The data indicates there are two types of massifs characterized by different ranges of radiometric dates. One type has a comparatively short duration (5-20 Ma), for example, Khibines, Lovozero (Kola Peninsula), and Guly (Maimecha-Kotuy Province, Siberian platform). Radiometric dates for the second type of massif indicates a range of about 400 million years (for example, the Kovdor massif, Kola peninsula; Tomtor massif, Siberian platform; the syenitic massif on Chichagoff Island, Alaska; the Quincy granites; and the White Mountain rock series in the Appalachian Province).

The sizes of the massifs are not related to duration of magmatic activity. For example, Khibines, Lovozero, and Guli massifs, are the largest in the world, but belong to the short-lived type, whereas the small Kovdor massif (Kola Peninsula), and the great Tomtor massif (Udja Province, Siberian platform) both belong to the group with the greatest range of radiometric dates. But the radiometric dates for each province as a whole have the same general range of several hundred million years. Moreover, for the most part, durations are in the order of 200 to about 400 Ma.

An explanation for the great range of radiometric dates for alkalic and ultramafic-alkalic provinces and the episodic character of magmatism was provided by Kumarapeli (1970) and later by Erlich (1985). They assume the earliest dates reflect the time of the first appearance of magma of a specific composition within a magma-generating zone in the upper mantle beneath ancient platforms. Thereafter, the magma persists at depth and each successive tectonic event is followed by a phase of magmatic activity of a related composition.

This explanation is supported by the well-known discrepancy between the radiometric ages of host kimberlites and ultramafic nodules. For example, Rb-Sr ages of unaltered peridotite nodules in Paleozoic kimberlite (Udachnaya pipe, Siberian platform) is 1,203 Ma. Rb-Sr age of peridotite nodules in Mesozoic kimberlite (Obnazhennaya pipe, Siberian platform), by mineral isochron data, is 370 Ma. Average Rb-Sr parameters for xenoliths from different pipes within the northeastern Siberian platform form a trend with a positive correlation coefficient of 0.97. Considering this dependence, as an isochron, it is possible to approximate an average age of deep-seated material beneath the kimberlites as 1,062 Ma (Zaitsev and others, 1983). The ages of serpentinized nodules from Yakutian kimberlites were also compared to the host kimberlite. Serpentinite nodules have Rb-Sr ages of 741 Ma, but Rb-Sr ages of the host kimberlite are 360 Ma.

U-Pb ages of two nodules in a kimberlite from the Chadobetsky uplift (southwest Siberian platform) are 1,600 ±150 Ma. However, one zircon grain from the Bol'shaya pipe in the same region was dated 810 ±150 Ma. The first date coincides with the time of stabilization of the platform. The second is near the age of the kimberlite bodies in the northeastern part of the Siberian platform (1,062 Ma) which, within the accuracy of the method, coincides with the time of the closing of the Ryphean aulacogens. The K-Ar dates for phlogopite nodules in kimberlites located within the northeastern Siberian platform are close to or even coincide with these dates. Additionally, close to these dates (or coincident with them) are radiometric ages of phlogopite calcifires from deposits connected with diopside metasomatites within the Aldan shield. These data indicate that the formation of the initial alkalic magma in the upper mantle correlates with the stabilization of the ancient platforms.

Similar results have been obtained in a study of the same material by different isotopic methods. For nepheline syenites of the Il'menogorsk region (Urals), U-Pb ages are from 400 to 280 Ma. By the model which proposes mobilization of radiogenic lead from chemically easily dissolved microinclusions in Th-U minerals (Krumm and others, 1984), concordant ages of zircons for miaskites and carbonatites equals 420 ±7 and 432 ±9 Ma, respectively. The age of discontinuity of U-Pb systems is accordingly dated back to 260 ±14 and 261 ±6 Ma (Chernyshov, Kononova, and others, 1984).The Rb-Sr isochron age of nepheline syenites in the same region is 450 Ma. Rb-Sr age of the second phase of nepheline syenites is 245 Ma (Krumm, and others, 1984). The authors of both studies concluded that two stages of formation of the massif occurred: the first was connected with Caledonian movements along the eastern margin of the Russian platform, and the second stage reflected amphibolite facies metamorphism in Permian time connected with the Herzinian stage of compression.

The shorter time of formation for the Ural's alkalic complexes in comparison to the cratons is probably related to more stable conditions within the cratons. It was shown above that the same shorter duration of range of radiometric dates is characteristic of alkalic magmatic complexes of Kruger Mountain in the Canadian Cordillera.

Data for some regions of North America indicates that there has been several overlapping periods of generation of ultramafic-alkalic and alkalic magmas.

In considering radiometric ages ranging in hundreds of millions years, it should be clear that we do not mean the duration of time of formation of a certain massif or intrusion, but instead of the time required for exhausting heat reserves within the roots of the asthenoliths of a given province.

If the conclusion as to constant time of alkalic and ultramafic-alkalic magmatic evolution is valid, then within any particular province exhibiting comparatively narrow time intervals for alkalic and ultramafic alkalic intrusions there must exist some intrusions of another age that have not been found. For example, all known intrusives in the Maimecha-Kotuy ultramafic-alkalic Province are dated as Permian-Triassic. However, it may be possible to find some blind intrusives of Ryphean age and some younger massifs of Jurassic age. The same may be possible for the Chadobetsky uplift region (southwest Siberian platform), Alaska Subprovince within the Cordillera Province.

Some practical consequences of the last conclusion are obvious: the presence of fragments of ultramafic-alkalic rocks in conglomerates and gravels within a certain region does not mean that ultramafic-alkalic rocks of younger age are absent. Carefully conducted exploration will be needed to locate hidden ultramafic-alkalic rocks of a younger age.

Within any province, different phases of ultramafic-alkalic rocks evolve in chemical composition through time from ultramafic-alkalic rocks to alkalic syenites and nepheline syenites (miaskitic or even agpaitic). Often a later second stage of ultramafic magmatism, in the form of dikes within the same province, will exhibit similar compositional variations through time. Such regularity probably reflects changes in composition and physico-chemical parameters within the stable platform's magma-generation zone beneath any alkalic and ultramafic-alkalic magmatic province.

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