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Paleomagnetism and Tectonics of the Kamchatka Region, Northeastern Russia: Implications for Development and Evolution of the Northwest Pacific Basin

By William Harbert[1], Pavel Kepezhinskas[2], Kirill Krylov[3], Vladimir Grigoriev[3], Sergei Sokolov[3], Maxim Aleksuitin[3], Alexander Heiphetz[4] and Paul Layer[5]

THEME 15: Geodynamics of the Arctic Region

Summary: The Kamchatka Peninsula of northeastern Russia is located along the northwestern margin of the Bering Sea and consists of zones of complexly deformed accreted terranes. Along the northern portion of the peninsula, progressing from the northwestern Bering Sea inland the Olyutorskiy, Ukelayat, and Koryak superterranes are accreted to the Okhotsk-Chukotsk volcanic-plutonic belt in northern-most Kamchatka. A sedimentary sequence of Albian to Maastrichtian age overlap terranes and units of the Koryak superterrane and constrains their accretion time with this region of the North America plate. Ophiolite complexes, widespread within the Koryak superterrane, are associated with serpentinite melanges and some of the ophiolite terranes include large portions of weakly serpentinized hyperbasites, layered gabbro, sheeted dikes, and pillow basalts outcropping as internally coherent blocks within a sheared melange matrix. Interpretation of magnetic anomalies allow the correlation of the Ukelayat with the West Kamchatka and Sredinny Range superterranes. The Olyutorskiy composite terrane may be correlated with the central and southern Kamchatka Peninsula Litke, Eastern Ranges and Vetlov composite terranes. The most „out-board" of the central and southern Kamchatka Peninsula terranes is the Kronotsky composite terrane, well exposed along the Kamchatka, Kronotsky and Shipunsky Capes. Using regional geological constraints, paleomagnetism, and plate kinematic models for the Pacific basin a regional model can be proposed in which accretion of the Koryak composite terrane to the North America plate occurs during the Campanian-Maastrichtian, followed by the accretion of the Olyutorskiy composite terrane in the Middle Eocene, and the Late Oligocene-Early Miocene collision of the Kronotsky composite terrane. A revised age estimate of a key overlapping sedimentary sequence of the Koryak superterrane, calibrated with new Ar^{40}/Ar^{39} data, supports its Late Cretaceous accretion age.

INTRODUCTION

The last ten years have seen significant advances in the comprehension of the structure, geology, and accretionary tectonics of the Northern Pacific Basin (CONEY et al. 1980, WOODS & DAVIES 1982, MOORE et al. 1983, ENGEBRETSON et al. 1985, SOKOLOV 1988, 1990, 1992, SOKOLOV et al. 1988, STAVSKY et al. 1990, KRYLOV et al. 1989, USTRITSKY & KHRAMOV 1987). Presently, interpretation of the geologic structure of this region is strongly linked with the paradigm of tectonostratigraphic terranes (CONEY et al. 1980, JONES et al. 1983). Tectonostratigraphic terranes are geologic zones that are fault bounded and have distinct geologic histories when compared with nearby localities (JONES et al. 1983). The names „Koryakia" or „Koryak Highland" refer to the Bering Sea region east of the Okhotsk-Chukotsk volcanic belt (OChVB), and south of the Chukotka block. Presently this region is part of the North America Plate, as this boundary is constrained by earthquake activity. Today, the plate boundary between North America and Eurasia plates is situated to the west from northern-most Kamchatka Peninsula going from the Lena delta area (Verkhoyansk sedimentary belt) to the western Okhotsk Sea (DEMETS 1992).

The region of northeastern Russia, referred to in the Russian language literature geographically as including the „Koryak Highland", in northeast Russia, consisting of the Kamchatka peninsula to the Gulf of Anadyr along the northwestern Bering Sea, has been interpreted as separate and distinct from the Mesozoic plutonic rocks of the Okhotsk-Chukotsk belt (in the Russian-language scientific literature referred to as the „Mesozoides of the Russian Far East") on the basis of the „absence of the granite layer in the crust", smaller crustal thickness and the presence of Tethyan (in the Russian-language scientific literature this term generally refers to an equatorial paleolatitude) fauna within the Paleozoic and Mesozoic Koryak highland region rocks (MIKLOUHO-MAKLAY 1959, BRAGIN 1992, 1988, BYCHKOV & CHEKHOV 1979, BYCHKOV & DAGIS 1984, BYCHKOV & MELNIKOVA 1985). These fauna are anomalous for their present-day high latitudes when compared with the Boreal fauna of the neighboring regions of Siberia within similar aged terranes (USTRITSKY & KHRAMOV 1987, SHAPIRO & GANELIN 1988, DAGIS 1993).

The formation of the Kamchatka peninsula by accretion and assemblage of oceanic and island-arc terranes, has been suggested during the last twenty years in the Russian-language scientific literature (ALEKSANDROV et al. 1975, 1980, ALEKSANDROV

[1] Department of Geology and Planetary Sciences, University of Pittsburgh, Pittsburgh, PA, U.S.A., <bill@earth.eps.pitt.edu>
[2] University of Southern Florida, Tampa, FL, U.S.A.
[3] Geological Institute, Russian Academy of Sciences, Moscow, Russia.
[4] Department of Geology and Planetary Sciences, University of Pittsburgh, Pittsburgh, PA, U.S.A.
[5] Geophysical Institute, University of Alaska, Fairbanks, AK, U.S.A.

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1978, Ruzhentsev et al. 1979, 1982, Byalobzhesky 1979, Alekseyev 1979, 1981, 1987, Kazimirov 1985, Gelman & Bychkov 1988). However, the entire northeastern region of the Russian Republic has only recently been interpreted to consist of accreted terranes (Fujita & Newberry 1982, Zonenshain et al. 1987, 1991, Grigoriev et al. 1990, 1992, Sokolov 1988, 1992, Stavsky et al. 1990, Astrahantzev et al. 1987, Grigoriev et al. 1986, 1987, Khanchuk et al. 1990, Krylov et al. 1989, Krylov 1990, Kazimirov et al. 1987, Didenko et al. 1993).

REGIONAL GEOLOGY OF THE KAMCHATKA PENINSULA

While more complex schemes have been proposed (Watson & Fujita 1985), in a simplified model, the region of Kamchatka has been divided into two main zones, the western (WZ, Western Zone Kamchatka superterrane) and eastern (EZ, Eastern Zone; East-Kamchatka superterrane) zones (Fig. 1). The boundary between these two regions is marked by a significant magnetic anomaly and a thrust system. This regional thrust, of western vergence in the northern part of Kamchatka, continues to the northeast where it may be traced to a major thrust system which divides the Koryak and Olyutorskiy superterranes. Much of the WZ complex consists of metamorphosed and strongly deformed, poorly dated, pre-Upper Cretaceous rocks of East and Central Kamchatka (Raznitsin et al. 1985, Tsukanov 1991). The EZ complex is made up of thick stratigraphic sections of Upper Cretaceous and Paleocene rocks, (Lower Eocene rocks in East Kamchatka), which have been thrust and folded. Intense deformation of this complex may be related to collision events of other terranes with the Kamchatka peninsula. A less-deformed complex is present in eastern-most Kamchatka, bordering the Pacific Ocean and Bering Sea. Folding and thrusting of pre-Pliocene rocks in a zone between Kamchatka and the Kronotsky Peninsula implies that the latter (geographically including the Kamchatka and Shipunsky Peninsulas) may be the youngest terrane accreted to the Kamchatka landmass (Fig. 1).

In the WZ, the Upper Cretaceous is represented by thick stratigraphic sections composed of turbidites. The source material for these deposits has been suggested to have been the Okhotsk-Chukotsk zone and an associated forearc. Volcanic material in sediments is scarce (at least in the Campanian-

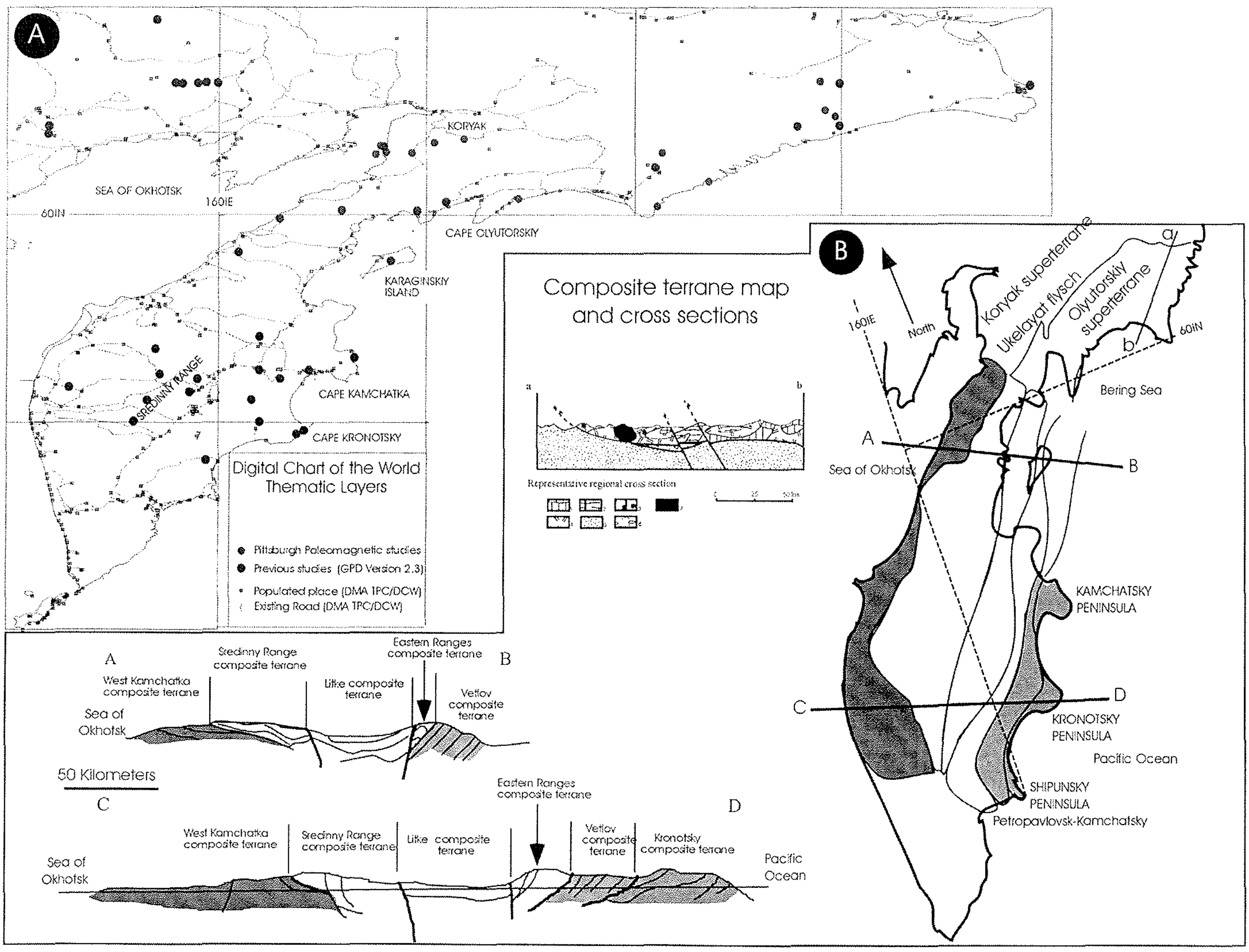

Fig. 1: Geographic reference showing paleomagnetic sampling sites, geographic names and roads in the Kamchatka Peninsula region. Simplified terrane diagram and three selected cross sections are shown.

Maastrichtian portion of the section); at the same time, blocks or lenses of basalt are common. The WZ is usually regarded as the marginal basin not far away from the continental margin.

In the eastern zone, EZ, volcanic flows (basalts, andesites, some associated sediments) are most common in the Late Cretaceous-Early Paleocene portion of the section. Some cherts and other silicious sediments are also found among volcanics (ZINKEVICH et al. 1990, TSUKANOV 1991, SHAPIRO et al. 1987, SHAPIRO 1976). Sedimentary formations of considerable thickness of Paleocene and Lower Eocene, sometimes Upper Senonian, are also present in this zone. The EZ can be divided into five composite terranes, 1) the Sredinny Range terrane, 2) Litke terrane, 3) East Ranges terrane, 4) Vetlov terrane, and 5) East peninsulas or Kronontsky terrane.

Jaspers and basalts of Santonian-Campanian age are the oldest rocks found in the Sredinny Range terrane (SHAPIRO et al. 1987). Using the geochemistry of volcanics as a guide, Soviet-era work suggests that these rocks are of oceanic (MORB) origin. Conformably overlying these are Campanian-Maastrichtian sediments, lava flows, and Upper Maastrichtian to Paleocene turbidites. These rocks are exposed in thrust sheets of western vergence. The eastern limit of the terrane is now hidden under late Cenozoic sedimentary cover of the Litke and Central Kamchatka basins but can be identified using regional residual magnetics.

The Litke terrane is mainly covered by late Cenozoic rocks with the exception of a limited area on a small Peninsula where the Upper Cretaceous island-arc series (flows and turbidites) outcrops (SHAPIRO 1976, KRAVCHENKO-BEREZHNOY et al. 1990, STAVSKY et al. 1990). The Litke subzone can be traced northward from Kamchatka into the Ilpinsky Peninsula of Koryak region, where tuffaceous Maastrichtian rocks are overlain without angular unconformity by thick Paleocene sequence.

Within the Eastern Ranges terrane the Upper Santonian to Maastrichtian interval is represented by volcanic flows, mainly basalts, and turbidites which are conformably overlain by Paleocene flysch. These rocks are deformed into folds and thrusts of western vergence and unconformably overlain by Middle Eocene sediments.

The Vetlov terrane is a narrow band of Paleocene-Eocene sediments and oceanic basalts deformed into thrusts of eastern vergence and unconformably overlain by middle Eocene sediments. The entire subzone has been interpreted to represent an ancient accretionary complex. As suggested by Soviet geologists, these volcanic and chert blocks immersed in a sheared terrigenous matrix may differ both in age and place of origin from the matrix. The zone is bounded on the east and west by large-magnitude trusts of eastern vergence.

The Eocene volcanic flow-sedimentary rocks of the Eastern Peninsulas, or Kronotsky terrane, are similar in the Kamchatka, Kronotsky and Shipunsky peninsulas, whereas older rocks on each peninsula are very different. For instance, the Cenomanian-Turonian part of the section on the Kamchatsky Peninsula consists of oceanic basalts with interbedded jaspers and pelagic limestones overlain by fine grained turbidites and arkoses (post-Turonian but pre-Maastrichtian in age), whereas Coniacian-Santonian volcanic and sedimentary rocks of an island-arc affinity are common on the Kronotsky Peninsula.

On the basis of composition, internal structure, age of rocks, and the age of the fault relationships, the geographical region of the Koryak highlands can be subdivided into three first-order superterranes, which moving inboard from the northwestern Bering Sea toward more interior Eurasia and the Okhotsk-Chukotsk volcanic plutonic belt and the associated forearc deposits (the Udsko-Murgalsky and the Taigonosky terranes), are the Olyutorskiy superterrane (OLY), Ukelayat superterrane (UKL) and Koryak superterrane (KOR).

The most outboard of tectonostratigraphic terranes which make up the northeast Kamchatka peninsula is the Olyutorskiy superterrane. A major southeastward-dipping thrust fault boundary, the Vatyna thrust, juxtaposes the Olyutorskiy superterrane (sometimes referred to as „Olyutorskiy zone“ or „Olyutorskiy system of nappes“ in the Russian-language literature (KAZIMIROV et al. 1987) to the south and the late Cretaceous to Paleogene-aged Ukelayat superterrane to the north (ERMAKOV & SOUPROUNENKO 1975, MITROFANOV 1977, ALEKSANDROV et al. 1980, MITROFANOV & SHELUDCHENKO 1981, ALEKSEYSEV 1987, ASTRAHANTZEV et al. 1987). The Olyutorskiy superterrane extends southward into Kamchatka where it is referred to as the East Kamchatka superterrane (East Kamchatka zone in the Russian-language literature) (SHAPIRO et al. 1984, SOKOLOV 1992, SOKOLOV et al. 1988) although the outcrops of older rocks between the Koryak and East Kamchatka superterranes are covered by Paleocene-Quaternary deposits. The Vatyna thrust extends into Kamchatka and is known in Kamchatka as the Lesnovsky thrust (SHAPIRO 1976, SHAPIRO & GANELIN 1988).

The Olyutorskiy superterrane in the northern-most Kamchatka region has been interpreted to represent an accretionary prism composed of at least three large, thrust fault bounded, terranes made of late Albian to Campanian oceanic basalts and Late Campanian(?) Maastrichtian-Paleocene island arc sedimentary, volcanic and plutonic units (ASTRAHANTZEV et al. 1987, KAZIMIROV 1985, KAZIMIROV et al. 1987, BOGDANOV & FEDORCHUK 1987, KRYLOV et al. 1989). In the central and southern Kamchatka peninsula, corresponding terranes have been described in the Sredinny, Valaginsky, Tumrok and Kumroch mountain ranges (SHAPIRO 1976, SHAPIRO et al. 1984, SOKOLOV et al. 1988, GRIGORIEV et al. 1990). The present interpretation of the Olyutorskiy superterrane is formation during the Late Campanian as an island-arc (in the Russian-language literature the Achaivayam terrane or Achaivayam island-arc) on Albian to Early Campanian age Kula plate oceanic sea floor basement (the Vatyna terrane). In this model, after northward motion on the Kula plate, at about 50 Ma, this composite terrane collides with, and is accreted to the Eurasia plate (ASTRAHANTZEV et al. 1987, KAZIMIROV et al. 1987, HEIPHETZ et al. 1994b).

The Ukelayat superterrane consists of a thick sequence of the Albian-Paleocene sedimentary-flysch rocks (ERMAKOV & SOUPROUNENKO 1975, MITROFANOV 1977, ALEKSANDROV et al. 1980, MITROFANOV & SHELUDCHENKO 1981, ALEKSEYSEV 1987, ASTRAHANTZEV et al. 1987). Following the same general regional structure as the Olyutorskiy superterrane, this superterrane strikes southwestward into the Kamchatka peninsula, where it is known as the West Kamchatka superterrane (West Kamchatka zone or Lesnovsky terrane in the Russian-language literature) (SHAPIRO & GANELIN 1988, SOKOLOV 1992, SOKOLOV et al. 1988, GRIGORIEV et al. 1990). Findings of the oldest fauna, Albian, are concentrated near the northern margin of the Ukelayat superterrane (within the Koryak mountains segment of this superterrane), or near western margin (within the Kamchatka peninsula segment). The lower part of the stratigraphic sequence in the central part consists of sub-arkose sandstones and mudstones which contain Santonian-Conjakian fauna (ERMAKOV & SOUPROUNENKO 1975, KAZIMIROV et al. 1987). The Late Cretaceous rocks consist mainly of graywakes turbidites interbedded with subarkose countourites. These are described in earlier Russian-language literature as a „two-component flysh" (ERMAKOV & SOUPROUNENKO 1975). Campanian units contain layers of jaspers and cherts, interbedded with mudstones. Several flows of the high-Ti MORB-like tholeiites have been identified interbedded with the Campanian sandstones (SHAPIRO & FEDOROV 1985, KAZIMIROV et al. 1987). Locally, Late Cretaceous sandstones are interbedded with coal deposits. The UKL superterrane has been interpreted as having been formed in a marginal, or back-arc, basin between the Achaivayam member of the Olyutorskiy superterrane and a continental plate (KAZIMIROV et al. 1987).

Continuing inboard from the Ukelayat superterrane, the Koryak superterrane is thrust over the Ukelayat superterrane from the north. The Koryak superterrane is a complex composite terrane which consists of many tectonostratigraphic terranes, including the Pekul'neisky (PKL) terrane, Mainitsky (MAN) terrane, Khatyrsky (KHA) terrane, Yanranaisky (YAN) terrane, Al'katvaamsky (ALK) terrane, Emravaamsky (EMR) terrane, Ganychalan (GNC) terrane, Upupkin (UPU) terrane, Ainyn (AIN) terrane, and Kuyul (KUY) terrane. These terranes vary in age from the Middle Paleozoic to the Early Cretaceous (SOKOLOV 1988, 1992). Thrusts within the composite superterrane appear to be overlapped by Albian to Maastrichtian and Late Albian to Paleocene age sedimentary rocks. In the western portion of the northern Kamchatka region, the Koryak superterrane includes (from northwest to southeast, progressing down the present-day tectonic section) the Ganychalan (GNC) terrane, Upupkin (UPU) terrane, Ainyn (AIN) terrane and Kuyul (KUY) terrane (MIGOVICH 1972, NEKRASOV 1976, SOKOLOV 1988, 1992, GRIGORIEV et al. 1990, KHANCHUK et al. 1990, HEIPHETZ & HARBERT 1992). The terrane boundaries are well expressed by regional magnetic and gravity field anomalies. Significant magnetic (HARBERT & HEIPHETZ 1992) and relatively high gravity (ALEKSANDROV 1978) anomalies allow calculation of the thickness of the Kuyul terrane. Models vary slightly, however generally all of the models Kuyul terrane are found to be that of a slab with thickness ranging from 0.9 km (ALEKSANDROV 1978) to 2.0 km (ALEKSEYEV 1981) dipping to northwest at 10 to 15°. A magnetotelluric profile across the southern border of the terrane suggests penetration of the terrane-bounding fault to depths up to 10 km with physical properties of the rocks differing significantly across this fault zone (MOROZ 1987).

Interpretation of residual magnetic field data using an algorithm which combines (as Red/Green/Blue color channels) the residual field, first horizontal derivative and second horizontal derivative to clearly define anomaly boundaries, has proved very useful in regional terrane correlation. The interpretation of these data supports the correlation of the Ukelayat with the West Kamchatka and Sredinny Range superterranes (Fig. 2). The Olyutorskiy composite terrane may be correlated with the Litke, Eastern Ranges and Vetlov composite terranes. The spatial extent of the most 'out-board' of the Kamchatka Peninsula terranes, the Kronotsky composite terrane, well exposed along the Kamchatka, Kronotsky and Shipunsky Capes is also clearly expressed by the residual magnetic anomaly data.

RADIOMETRIC AGES

Samples from four basalt blocks within the melange of the Koryak superterrane (the Gankuvayamsky terrane), one basalt flow and one basaltic dike were dated by Ar^{40}/Ar^{39} step-heating analysis at the University of Alaska Geochronology Laboratory (Tab. 1). Approximately 0.25 g of crushed whole-rock sample was irradiated at the McMaster Nuclear Reactor for 70 MWh along with standard hornblende MMhb-1 with an age of 513.9 Ma (LANPHERE et al. 1990). The results of the dating experiments are shown in Table 1 with all ages determined using the constants of STEIGER & JAEGER (1977). Sample 1/18, a basaltic dike had less than 0.01 wt.% K_2O and hence was unsuitable for dating. K_2O contents of the basaltic blocks range from 0.1 to 0.54 wt.% while the basaltic flow contained 1.50 wt.%, allowing for

Sample	Rock	Mass	Number of Fractions	Integrated Age (Ma.)	Interpreted Age (Ma.)
1/18	Basaltic Dike	0.2804	9	84.7±39.1	Insufficient K for analysis
1/5	Basaltic Flow	0.2154	9	76.2 ± 0.3	74.3 ± 2.4
1/33	Basaltic Flow	0.2409	9	120.0 ± 0.7	121.7 ± 0.8
1/56	Basaltic Flow	0.2410	8	102.2 ± 2.1	96.9 ± 1.7
1/31	Basaltic Flow	0.2297	9	109.2 ± 1.5	108.0 ± 1.8
1/55	Basaltic Flow	0.2473	8	92.0 ± 3.4	93.6 ± 2.7

Tab. 1: Ar^{40}/Ar^{39} results, Kuyul terrane, northeastern Russia. Samples run against standard MMhb-1 with an age of 513.9 Ma and processed using the constants of STEIGER & JAGER (1977). K_2O and CaO values (in wt.%) are not calibrated and are for reference only.

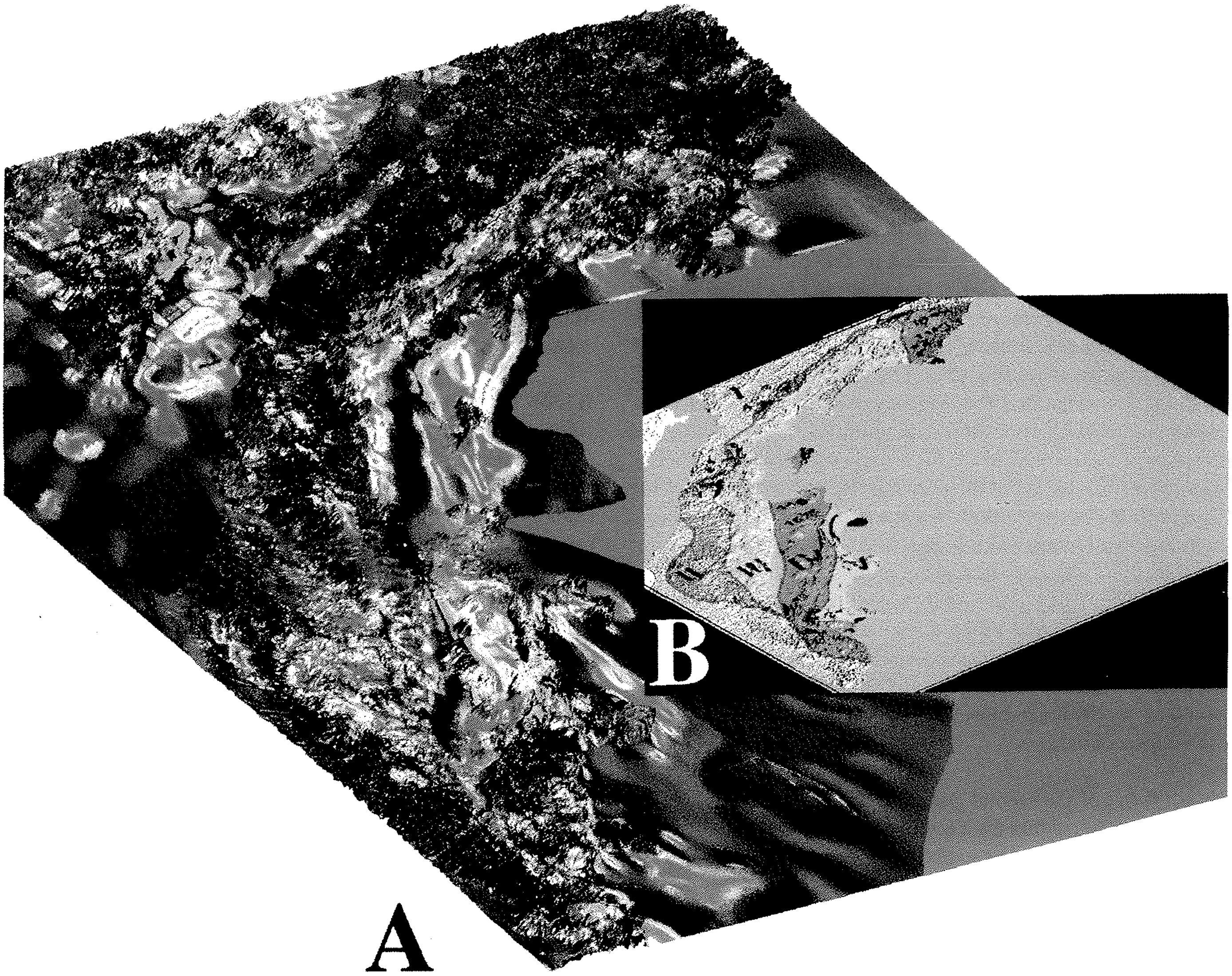

Fig. 2: Horizontal slope of residual digital magnetics (A) for the Kamchatka peninsula draped on a NIMA Level 0 DEM for this region. White regions are those which have maximum horizontal slopes and can be interpreted to link terrane structure on the central Kamchatka peninsula with that in the Koryak/Olyutorskiy regions of the northern Kamchakta peninsula. For comparison a georeferenced terrane map is shown draped on a Digital Elevation Model (DEM) of this region (B).
The terrane map was downloaded from the Academy of Sciences of Russia Geological Institute "Virtual Kamchatka" web page). Major terrane boundaries shown on Figure 1 are clearly visible in the regional residual magnetics and verify the major boundaries as proposed by previous workers.

fairly precise determination of the age of these samples. Samples from basaltic blocks all have similar age spectra with age plateaus comprising 65–76 % of Ar^{39} release. Samples 1/56 1/31 and 1/55, from the larger, southern melange belt have ages around 100 Ma although there is some significant deviation about this age. Sample 1/5 from the basaltic flow unit shows a stairstep-down age spectrum. Isochron analysis yields an age of 74 Ma, an age which probably represents either the time of formation of the basalt on the sea floor or the emplacement of the basalt-dike zone.

These ages are significantly younger than the ages for these terranes determined from interbedded fossils (Late Bathian to Early Callovian complexes of radiolaria *Tricolocapsa cf., Parvicingula burnensis* Pessagno and Whalen, *Dicolocapsa conformis* Matsuoba, *Amphipyndax duriseptum* Aita, *A. tsunoensis* Aita and Titonian complex *Pseudodictyomitra* Matsuoka and Yao, *P. cf. carpatica* Losyniak are found in the jasper lenses, generally associated with pillow basalt and constraining their age, all fossil determinations by V. Vishnevskaya, Institute of Lithosphere, Moscow). We interpret the new radiometric ages to more accurately represent the age of the sampled units. As an example of the potential divergence of newer radiometric ages, paleontological ages and older Soviet-era radiometric ages, there is a Paleozoic date of 324 ±3 Ma within this terrane, obtained using the K/Ar method from a hornblende extract from a plagiogranite dike within the sheeted dike complex (KHANCHUK et al. 1990) in the ultramafic rocks and layered gabbro.

DISCUSSION OF GEOCHEMISTRY

FEDORCHUK (1987) divides the basalt flows of Vatyna structural unit into two groups of the Olyutorskiy superterrane. The first group consists of flows located in the lower part of the stratigraphic sequence and is characterized by lower than in average basalt concentration of SiO_2 (46-50 %, with average of 49 %) compared to relatively high sum of Na_2O and K_2O (3-5 %, with average exceeding 4 %). Therefore they were classified as alkali olivine basalts. The tendency of increasing Na_2O+K_2O, especially of K_2O, concentrations with decrease of SiO_2, and location of these rocks in the high-magnesium area of the Hawaiian trend on the AFM diagram are also characteristic for the alkali olivine basalts series. The basalt of the first group has a high K_2O/Na_2O ratio (0.2), higher than usual concentrations of titanium (TiO_2 concentration averages about 2 %) and phosphorous (0.3 % of P_2O_5), and slightly higher concentration of Al_2O_3 (over 16 %). Ratios of lithophil elements show the increase in concentrations of the most incompatible elements, i.e. these rocks are characterized by high Zr/Y and Ti/V ratios (4-6 and 40-60 respectively) and low TiO_2/P_2O_5 and Ti/Zr ratios (4-6 and 70-90 respectively).

Basalt flows of the second group occupy the uppermost stratigraphic position within the Vatyna thrust zones. These are much more differentiated rocks with SiO_2 varying between 44-55 %. With the increase of F -parameter (F = FeO*/(FeO* + MgO), where FeO* = Fe_2O_3 + 0.9*Fe_3O_4) from 1.1 to 1.6, the concentration of SiO_2 decreases from about 48 to about 44 %. However when F -parameter increases further, the SiO_2 trend reverses and SiO_2 concentration increases to 51-55 %. At the same time (with increase of the F -parameter) concentrations of Al_2O_3 decreases rapidly from 16 to 12 % and total iron (FeO* = Fe_2O_3 + 0.9*Fe_3O_4) concentrations increase from 12 to 15 %. Unlike basalt of the first group, basalt of the second group have very low potassium (0.02-0.6 % K_2O); potassium also does not have tendency to increase with increase of F -parameter. This kind of chemical composition defines tholeiitic trend of this group on the AFM diagram, parallel to the FM side of the triangular. Composition of the basalt of the second group are typical of the ferro-basaltic series. This conclusion is also supported by high TiO_2 (over 2.2 %), P_2O_5 (0.2-0.3 %) and high TiO_2/P_2O_5 ratio (about 11 at average). Basalt flows of the second group also differ from the basalt flows of the first group by high concentrations of Zr, Y and V (150-230, 40-70 and 300 ppm respectively). Zr/Y and Ti/V ratios (3-4 and 45-55 respectively) are lower and Ti/Zr ratio (90-100) is higher than in the basalt flows of the first group. Trends of differentiation of K, P, Rb, Sr and Ba with respect to F -parameter continue those of the basalt flows of the first group, although at higher values of the F -parameter. Concentrations of Rb (7 ppm), Ba (140 ppm) and Sr (230 ppm) in these rocks are lower than in the basalt flows of the first group, although they are significantly higher than in typical Mid-Ocean Ridge Basalts (MORBs).

When studying Zr/Y vs. Zr, Ti/Cr vs. Ni and Ti vs. V relationships, (FEDORCHUK 1987) the Vatyna basalt of both groups originated from a mantle source enriched in lithophile elements. Alkali-olivine (of the first group) or ferro-basaltic (of the second group) composition of these rocks differentiates them from the typical Mid Oceanic Ridge Basalts (MORBs). Basalt flows of both groups are most close to the intra-ocean plate basalts. On the basis of the geochemistry of the basalt flows of the Vatyna structural unit FEDORCHUK (1987) suggested that they formed within an „intra-plate volcanic rise originating over older oceanic crust“.

Within the Koryak superterrane, the Vesely and Gankuvayamsky terranes have different geochemical composition and contain fauna of different age, Triassic to Upper Jurassic, in the Vesely terrane and Bathonioan and Callovian in the Gankuvayamsky terrane. Within the Vesely terrane there are igneous rocks of two types, N- (Normal) and E (Enriched)-MORB with N-MORB's the most common. These data can be interpreted to suggest that the Vesely terrane basalts formed in two adjacent tectonic environments, at a mid-oceanic ridge, and within the ocean plate in the basement of seamount(s). The association of these igneous rocks with pelagic limestones and jaspers, as well as their MORB geochemistry, suggests this interpretation. This is also supported by mineral composition of ultramafic rocks of the melange, which contain basaltic blocks. These are slightly depleted peridotites, similar to oceanic lhertzolites, and very primitive lhertzolites, similar to lhertzolites of oceanic islands and passive margins (personal communication by V. Batanova and A. Peive 1993). Some enriched compositions of E-MORB igneous samples may correspond to these primitive ultramafic compositions. The volcanic breccia rocks within the Vesely and Gankuvayamsky terranes have strong similarities to the Vesely terrane N-MORB igneous samples, although their association with fault-disrupted olistostromes and pelagic red mudstones may suggest their formation along an oceanic plate transform fault.

The Gankuvayamsky terrane contains igneous rocks of at least four distinctive types, tholeiites similar to N-MORB's of the nearby Vesely terrane, CA basalts, andesites and dacites, and boninites. Because CA and plagiogranite dikes intrude the tholeiite ones (LUCHITSKAYA 1995) within the Vesely terrane sheeted dike complex the CA series rocks appear to be of a relatively younger age. Diagrams showing the ratios of the LIL (Large Ion Lithophile) elements to the HFSE (High Field Strength Elements) vs. HFSE (e.g. Ba/Y-Ba, La/Zr-Zr) and the distribution of REE (Rare Earth Elements) suggest melting of these rocks from a similar mantle source under different conditions. The presence of water-containing minerals (hornblende) in the acid fractions of CA series rocks (KHANCHUK et al. 1990, KRYLOV & GRIGORIEV 1992) suggests that the CA series rocks formed under higher fluid pressure. Significant fluid pressure may be responsible for the high degree of fractional differentiation and volume of the acid differentiates (about 15-20 %). The acid differentiates are enriched in LIL elements and depleted in HFSE (Zr, Y, Nb, etc.).

We interpret these Gankuvayamsky ophiolite geochemical data from the CA and boninite series rocks to suggest that they formed within a suprasubduction zone of Late Bathonian to Early Callovian and Titonian age. Recent study in the Idzu-Bonin island-arc system showed that boninites are typical for the forearc spreading environments at the early stages of the development of subduction zones. In our model the Gankuvayamsky ophiolites were formed along the subduction-zone side of a young island-arc in the forearc basin area. Volcanics of the tholeiite series of the Gankuvayamsky terrane are geochemically indistinguishable from the tholeiites of the Vesely terrane.

INTERPRETATION OF PALEOMAGNETIC DATA

Koryak superterrane: Data from the Khatyrka terrane (KO and RY), Kuyul (GA1), Maynitsky terrane (YA), and sedimentary overlap sequences (SE, UB and PB) constrain the Late Paleozoic and Mesozoic paleolatitudes of these terranes (Fig. 3, Tab. 2). Each of the paleolatitudes from the Khatyrka and Maynitsky terranes are anomalously low. The paleomagnetic pole from the Senonian and Cenomanian-Maastrichtian sedimentary sequences suggests deposition of these units at the expected, with respect to either North American or Eurasian Apparent Polar Wander Paths (APWP), paleolatitudes thus providing a minimum estimated accretion age for the overlapped terranes.

Within the Khatyrka terrane the observed paleomagnetic paleolatitude is 24 °N or S for the island arc complex of the Upper Triassic aged KO. The observed paleomagnetic paleolatitude from the Jurassic-Cretaceous, RY is 22 °N or S, and 25 °N or S for GA1.

The ophiolite rocks studied in the Maynitsky terrane also differ significantly in paleolatitude when compared with that expected for either the Eurasia or North America plates. The paleolatitude calculated from the YA of the Maynitsky superterrane yields a paleolatitude of 32 °N or S, significantly shallower than expected using either EUR or NAM APWP reference data.

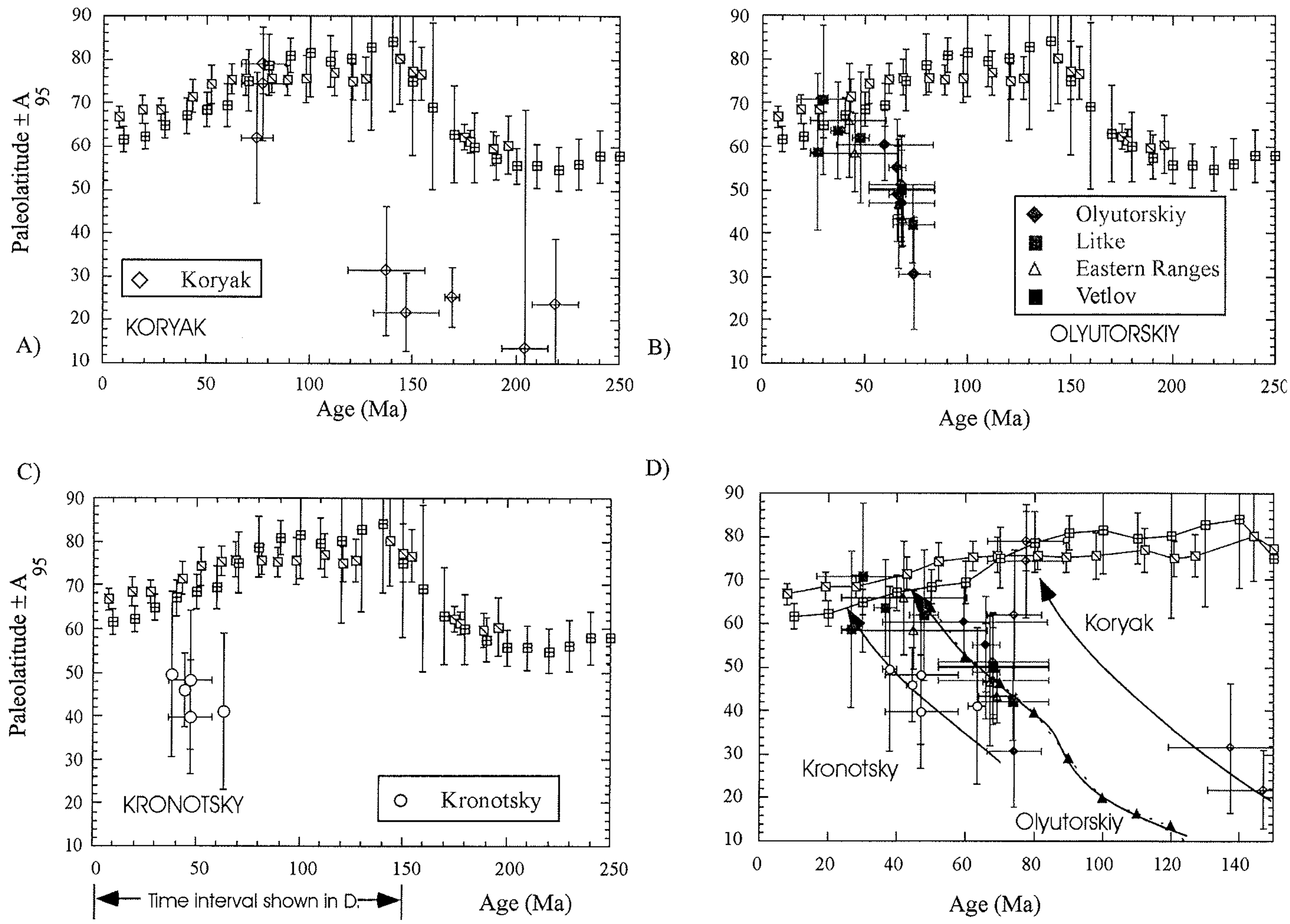

Fig. 3: Interpretation of paleomagnetic data with respect to expected paleolatitudes for representative sites on the North America plate and modeled paleolatitudes assuming displacement histories on oceanic plates in the paleo-Pacific basin. Expected paleolatitudes for a reference point on the Kamchatka Peninsular are shown using the APWP data of BESSE & COURTILLOT (1991) (Box with internal slash) and IRVING & IRVING (1982) (Box with internal cross). Numeric data are shown in Table 2.

Locality	Age	Loc °N/°E	N	Demag/Test/Pol	D_S	I_S	$\alpha 95$	$\lambda_{obs} \pm A95$	Terrane
UB	Senonian	63.0/179.5	13	AF / ? / M	263	82	13	74.3°±13°	Al'Kat-vaamsky-Koryak
PB	Cenomanian-Maastrichtian	61.5/164.0	10	AF / ? / M	61	75	15	61.8°±15°	Ainyn-Koryak
UA	66±4 (K/Ar)	61.5/170.5	15	TH / F / R	321.4	70.8	10.8	55.1°±11°	Olutorskiy
MB	66±4 (K/Ar)	60.8/171.6	16	AF+TH / F / N	336.0	66.5	10.5	49.0°±11°	Olutorskiy
JB	Campanian	60.2/170.4	17	AF+TH / F / N	297.6	49.9	12.9	30.7°±13°	Olutorskiy
VIII	K cp-m	60.3/170.6	??	TH / F / M	97	68	5	51.1°± 8°	Olutorskiy
VII	K^2 cp-m	60.8/170.0	??	TH / F / M	88	65	5	47.0°± 8°	Olutorskiy
VI	K^2 cp-m	61.6/171.2	??	TH / M	80	67	8	49.7°± 13°	Olutorskiy
XIII	P^2	60.7/168.0	??	TH / F / M	348	74	4	60.2°± 8°	Olutorskiy
YA	L^2. Jur-E.Cret	63.2/174.3	5	TH / F / N	201.2	50.7	15.3	31.4°±15°	Mainitsky-Koryak
KO	L. Triassic	62.5/174.5	5	TH / F / M	186.5	41.5	15.4	23.9°±15°	Khatyrsky-Koryak
RY	L. Jurassic	62.4/174.8	4	TH / F / N	47.9	38.7	8.8	21.8°±9°	Khatyrsky-Koryak
SE	Senonian	62.5/174.4	5	TH / F / N	5.5	84.4	6.9	78.9°±7°	Overlap Sequence Koryak
GA1	L. Bathonian-Callovian	61.5/164.6	15	TH / F / M	34.6	43.5	7.1	25.4°±7°	Kuyul- E. Korya
GA2	93.6±2.7	61.5/164.6	4	TH / F / N	273.4	87.3	23.1	84.6°±24°	Gankuva-yamsky-Koryak
KMP	63.5±2.5	56.3/163.3	5	TH / F / M	28.0	60.2	12	41°±.18°	Krontsky
KME1	44.5±1.5	56.5/163.3	7	TH / F / M	18.8	64.5	5.3	46°±.4 9°	Krontsky
KME2	38±2	56.5/163.3	1	TH	359.4	66.9	11.2	49.5°± 19°	Krontsky
KMR	Campanion-Lower Paleocene	56.6/162.3	5	TH / F / R	337.5	67.4	7	50.2°± 12°	Vetlov
KMR1	Oligocene-Miocene	56.2/162.2	21^+	TH / R	310	54	7	34.5°± 10°	Post-accretionary Complex
KP1	Eocene	56.5/163.3	31^+	TH / N	18	66	10	48.3°± 16°	Kronotsky
KRP	Eocene	54.8/162.1	4	TH / F / M	310	59	9	39.8°± 13°	Kronotsky
IXX	K_2m-d	59.0/164.5	??	TH / F / M	332	62	5	43.2°± 6°	Eastern Ranges
XV	P^3 - P^1	60.0/165.0	??	TH / F	338	80	9	70.6°± 17°	Litke
XVII	P^{2_2} ^{3}	59.8/164.9	??	TH / F	299	73	10	58.6°± 18°	Litke
XIV	P^{2_1}	60.0/165.2	??	TH / F / M	321	76	6	63.6°± 11°	Litke
XVIII	P^{2_2}	59.8/164.8	??	TH / F / M	285	75	8	61.8°± 15°	Litke
XVI	K^1 cp-d	60.0/164.9	??	TH / F /M	299	61	6	42.1°± 9°	Litke
KA	66±4 (K/Ar)	59.0/164.2	3	TH / F / M	330.3	64.8	15.0	46.7°±15°	East Kamchatka*
MA	L. Paleocene-Oligocene	60.4/167.1	5	TH / F / M	353.6	77.4	12.7	65.9°±13°	East Kamchatka*
IL	Paleogene	59.8/164.9	10	TH / F / M	307.3	72.9	8.8	58.4°±9°	East Kamchatka*

Tab. 2: Selected Paleomagnetic data from the Kamchatka region, northeastern Russia. References: Pechersky (1970) UB, PB; Bazhenov et al. (1992), KMR, KP1, KRP; Heiphetz et al. (1993b) UA, MB, JB; Didenko et al. (1993) YA, KO, RY, SE; KA, MA, IL; Heiphetz et al., (1993a) GA1, GA2; Pechersky et al. (1997) KMP, KME1, KME2; Levashova et al. (1997), KMR; D.V. Kovalenko (personal communication 1998) VIII, VII, VI, XIII, IXX, XV, XVII, XIV, XVII, XVI; $^+$Statistics calculated using N = number of samples; * East Kamchatka superterrane can be correlated with the Olutorskiy superterrane.

These paleolatitudes are consistent with each other but differ significantly from those expected for either the Eurasia or North America plates. These results strongly suggest that the Khatyrka terrane is both far-traveled and allochthonous with respect to this region of the northeastern Russia. We cannot, on the basis of these data alone, specify whether these paleolatitudes represent northern or southern hemisphere latitudes of deposition. Either interpretation, when compared with expected paleolatitudes for the North America or Eurasia plates, show substantial northward motion of this superterrane.

The paleomagnetic data from the Senonian and Cenomanian-Maastrichtian age overlap sediments of the Al'katvaamsky terrane (UB), Penzhina Bay (PB) and Khatyrka terrane (SE) suggest that these sediments were deposited at high paleolatitude, along the southeastern edge on the Eurasia plate. There is no significant difference between the expected and observed paleolatitudes. This suggests that accretion of the Koryak superterrane occurred prior to Senonian-Cenomanian-Maastrichtian time.

Olyutorskiy superterrane: The difference between the UA, MB, and KA localities paleolatitudes for Late Cretaceous-Paleocene are insignificant at the 95 % confidence limits and consistent with paleomagnetic results VIII, VII, and VI (Tab. 2). Nevertheless, these localities are contained in different fault bounded structural zones. Paleomagnetic data of older age, JB, and younger age, IL and MA are also available for interpretation.

Comparing studies UA and MB with the appropriate APWP from Irving & Irving (1982), comparison with Besse & Courtillot (1991) yield similar results, we find a latitudinal anomaly of 23.0° ± 18.0° for the UA and of 28.3° ± 17.0° for the MB localities suggesting that Maastrichtian tuffs and tuffaceous sandstones originated significantly to the south of either reference plate. Rotational and flattening statistics (Demarest 1983) calculated with respect to the 67 Ma North America paleomagnetic reference pole (Irving & Irving 1982) show that these rocks should have formed at a significant distance from the North America continent. Calculated latitudinal anomaly are 20.5° ± 14.7° for the Upper Apuka and of 26.2° ± 13.4° for the Machevna Bay localities. The choice of the paleomagnetic reference pole (reference continent) does not effect to the interpretation of the displacement: the Maastrichtian island-arc where these rocks originated was situated 20° - 30° south from both North America and Eurasia continents.

The JB result is significantly shallower than expected from either APWP, with an observed paleolatitude of 32° and a difference between expected and observed paleolatitudes of 42.6° ± 21.8° (Tab. 2). In order to model these observed paleolatitudes we have used plate kinematic models of the past motions of oceanic and continental plates in the Northern Pacific Basin (Engebretson et al. 1985) and the modeling techniques described in Debiche et al. (1987).

To model the UA, MB, KA, and JB paleomagnetic results and the associated paleolatitudes we constructed model apparent polar wander paths [MAPWP] using the techniques of Debiche et al. (1987). This method consists of rotating APWP reference points into a terrane frame of reference using finite rotations between the Eurasian and the ancient Izanagi and Farallon oceanic plates. In addition we use the finite rotations (Engebretson et al. 1985), used to construct the MAPWP, to calculate the corresponding terrane trajectories for the UA, MB, KA, and JB localities of the Olyutorskiy Peninsula.

The key assumption in constructing either a MAPWP or terrane trajectory is the location and age of accretion (Debiche et al. 1987). The age of accretion of the Olyutorskiy superterrane is estimated to be Late Eocene to Miocene on the basis of the initiation of the shallow water sandstones and mudstones of this age overlapping terrane bounding thrust faults. This age constraint includes more than 30 Ma of the time and alone is not precise enough for terrane trajectory modeling. However, we can use paleomagnetic data as a check of validity of a model. We constructed two terrane trajectory models assuming the age of accretion to be either 40 Ma or 50 Ma. Other assumptions remained the same in both models. To model the paleomagnetic results we assumed a displacement history for the terrane that consists of the Olyutorskiy superterrane as being transported with the Izanagi plate between 90 and 85 Ma followed by Kula plate motion between the beginning of Campanian (~85 Ma) and the time of accretion (in the 40 Ma accretion model, motion with the Pacific plate occurs between 43 and 40 Ma). We find that the expected paleolatitude corresponding to this displacement history is significantly shallower than paleomagnetic results (in the 40 Ma accretion model) but closely matches our paleomagnetic results in the 50 Ma accretion model. Assuming the latter displacement history and collision to North American plate we expect a paleolatitude of between 58 and 46 °N at 60 to 70 Ma and a paleolatitude between 39-52° at 90 to 80 Ma, closely matching the observed paleomagnetic data from the Olyutorskiy superterrane.

Together these new paleomagnetic results and their close agreement with the calculated terrane trajectories strongly suggest that an island arc system moving with the Kula plate collided with this region of North American plate approximately 50 Ma (Middle Eocene). Engebretson et al. (1985) and Debiche et al. (1987) have suggested such a subduction boundary between the Izanagi and Farallon plates. In the model of Engebretson et al. (1985) this region becomes part of the Kula plate at 85 Ma, after initiation of Kula-Farallon motion. Our data show that fragments of an island arc are present in the Olyutorskiy superterrane and East Kamchatka superterrane as predicted by this model, perhaps the tectonostratigraphic terranes of the northern Kamchatka represent an accreted fragment of an oceanic island arc system between the Izanagi and Kula plates.

The coincidence of this age of accretion (approximately 50 Ma) and the age of initiation of subduction along the Aleutian arc (estimated as Late Paleocene to Early Eocene) suggests the possibility of a causal relationship. When the colliding Olyutorskiy composite terrane obducted onto the margin, significant stress may have occurred within the region northwestern Pacific basin subduction zone stressing regions of the subducting plate. The small circle geometry of the present day Aleutian arc and the right angle intersection of magnetic anomalies interpreted, over the oceanic plate presently beneath the eastern Bering Sea, with the arc both strongly suggest that the region now occupied by the Aleutian arc subduction zone was originally a transform fault within an oceanic plate. Given this pre-existing zone of weakness within the subducting oceanic plate and its apparent close proximity to the region undergoing obduction of the Olyutorskiy superterrane during the Early Eocene, we strongly favor this model for formation of the present-day Aleutian arc subduction zone.

Kronotsky superterrane: The final episode of terrane accretion with the Kamchatka Peninsula is recorded by paleomagnetic results collected from Cape Kamchatka and Cape Kronotsky. These paleomagnetic results show significantly shallower than expected inclinations when compared with the expected directions calculated from the North America APWP and suggest minimum poleward rates of motion of approximately 5 cm/yr. Docking of these terranes appears to have occurred at approximately 30 Ma, although coastwise transpressive strike-slip motion of portions of these terranes may have occurred.

CONCLUSION

Geological mapping, geochemistry and paleomagnetism suggests that the Kamchatka Peninsula consists of a collage of accreted terranes. Geochemical data from the Koryak and Olyutorskiy superterranes are compatable with the formation of these superterranes in an oceanic-plate/island arc setting. New Ar^{40}/Ar^{39} ages calculated within the Kuyul terrane, suggest the possibility for significantly younger (Late Cretaceous) geologic ages than previously proposed for some units in this terrane. Overall thirty-one paleomagnetic studies support a model in which punctuated accretion (docking) events of three composite or superterranes with the North America plate occur as following -Koryak superterrane- 80 Ma, Olyutorskiy superterrane 50-40 Ma, Kronotsky superterrane 20-30 Ma. Paleomagnetic data for the Olyutorskiy and East Kamchatka superterranes, combined with terrane trajectories calculated using the finite rotation poles of Engebretson et al. (1985) support a model which includes a subduction zone between the Izanagi and Farallon plates. The obduction of the Olyutorskiy superterrane with the North America plate in the Kamchatka region probably initiated a jump in subduction away from the North America plate margin in this region to a relic transform fault resulting in formation of the present-day Aleutian arc.

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