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Towards a More Complete Record of Magmatism and Exhumation in Continental Arcs, Using Detrital Fission-Track Thermochrometry

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Abstract. The NE Asian margin was the locus of an Andean-style subduction zone during most of the Mesozoic and Cenozoic. The Ukelayat flysch is a 10 to 15 km thick section of marine turbidites that were deposited in a 500 km long forearc basin along the outboard edge of this convergent margin. It was structurally overridden during the early Tertiary by an obducted island arc, the Olytorsky terrane. We present new fission-track (FT) grain ages from unreset detrital zircons. These data provide precise information about depositional age of the Ukelayat and the temporal evolution of the Asian margin continental arc, which provided much of the sediment for the Ukalayat. Because all sandstones contain a large fraction of first-cycle volcanic zircons (euhedral, colorless), we infer that the youngest component of the FT grain age distribution, designated P1, closely approximates the time of deposition. Twenty-seven samples have yielded P1 ages ranging from ~44 to 88 Ma, which indicates continuous magmatic activity in the arc from the Late Cretaceous to Middle Eocene. A second component (P2) records progressive exhumation of the basement to the Okhotsk-Chukotka arc. The difference between P1 and P2 ages indicates steady exhumation at ~200-400 m/Myr from ~90 to 44 Ma. This finding implies the removal of 9 to 18 km of rock in the most deeply exhumed parts of the source region. A change in exhumation rates at ~70 Ma may coincide with an eastward shift in the locus of volcanism from the Okhotsk-Chukotka arc to the younger Western Kamchatka-Koryak arc.

1 Introduction

Terrigenous sediments provide a nearly complete record of orogenesis in continental settings. Detrital thermochronology provides one method for reading that record because the fission-track (FT) method can be used to date single grains in siliciclastic sandstones (Garver et al., 1999a). Zircon is the most common target, given its common presence in crustal rocks of the source region and its stability during transport and diagenesis. Where sandstones have remained at < ~200 C after deposition, the detrital zircons will retain age information about cooling events in the source region. By dating 50 to 100 grains from a single sandstone sample, one can assemble a reliable sample of the fission-track grain-age (FTGA) distribution. Different age sandstones can then be used to assemble a stratigraphically coordinated set of FTGA distributions, which can provide a detailed view of how the source region evolved with time.

In this study, we use detrital zircon FTGA distributions to study a major sedimentary unit, the Upper Cretaceous-Eocene Ukelayat flysch, which is exposed for some 500 km along the Kamchatka Peninsula in the Russian Far East. The unit is thought to have formed in a forearc basin setting along the NE Asian margin. The descriptive term "flysch" is appropriate given the predominance of marine turbidities in this thick sedimentary sequence. The Ukelayat is important for two reasons: 1) It structurally underlies the Olyutorsky terrane, a regionally extensive Upper Cretaceous island arc that overrode the NE Asian margin sometime during the early Tertiary. This event is considered to be the precursor for initiation of the modern Kamchatka-Aleutian subduction zone. Ages from the Ukelayat can be used to better constain the timing of collision, but sparsely fossiliferous nature of the Ukelayat have made this approach difficult. 2) The Ukelayat contains a relatively complete record of subduction-related arc magmatism. Stratigraphic studies within the more inboard magmatic belts suggest that there may have been a hiatus in subduction along the northeast Asian margin during the latest Cretaceous and early Tertiary (e.g., Filatova, 1987; Stavsky et al., 1990). Ukelayat sandstones contain a large fraction of first-cycle volcanic zircons. Thus, FT ages of these zircons can be used to new information about the duration of subduction-related magmatism.

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2 Regional Tectonic Setting

The Ukelayat flysch formed at the NE Asian margin during the Cretaceous and early Tertiary. Three contrasting coeval tectonic features are relevant to the evolution of the margin at that time: 1) an inboard set of continental magmatic arcs, which represent the source for Ukelayat sediments; 2) the Ukelayat flysch, which was deposited at the perimeter of the NE Asian margin, and 3) a far-traveled oceanic arc, which was obducted on the Ukelayat during an early Cenozoic accretionary event.

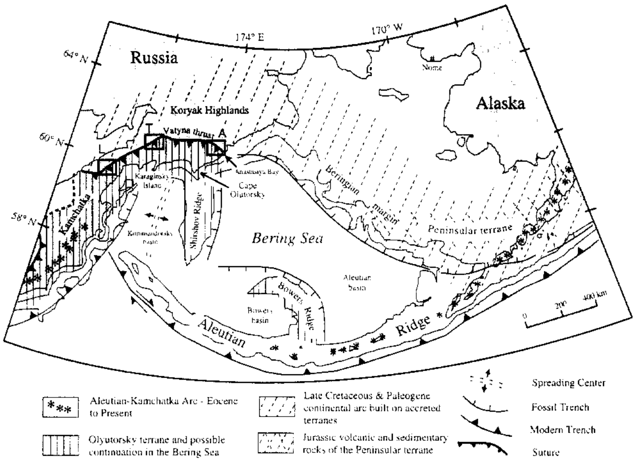

Fig. 1: General geologic setting of the Koryak Highlands with respect to Kamchatka and the Bering Sea. The Olyutorsky terrane lies outboard of the Vatyna fault and is well exposed in northern Kamchatka. Similar rocks are found in southern Kamchatka, but they are partly obscured there by young volcanic cover. Offshore, the Olyutorsky terrane may include the Shirshov and Bowers Ridge. The trenches that border the north of the Bowers Ridge and the south side of the Berginian margin are thought to have been active until collision of the Olyutorsky terrane. The box shows the location of Figure 2. Modified from Cooper et al., 1987, Stavsky et al., 1990, and Worrall, 1991.

2.1. Continental arc and associated basement

The Cretaceous Okhotsk-Chukotka magmatic arc extends from the Sea of Okhotsk, across Chukotka and the Bering shelf, and into western Alaska (Fig. 1). This Andean-style magmatic arc was built on a basement of older oceanic terranes accreted to the NE Asian margin from Late Jurassic to mid-Cretaceous (Stavsky et al., 1990; Nokleberg et al., 1998). Limited K-Ar and fossil ages indicate most rocks are Cretaceous, although some early Tertiary ages have been reported (Filatova, 1987; Stavsky et al., 1990). The West Kamchatka-Koryak volcanic belt, which is early Tertiary in age, records a trenchward (southeastward) shift in arc magmatism. This shift might indicate an increase in slab dip at that time (Stavsky et al., 1990). Available age data suggest a 10 to 20 m.y. gap between the Okhotsk-Chukotka arc, which is thought to have stopped at the end of the Cretaceous, and the West Kamchatka-Koryak belt, which was initiated in the Eocene. This hiatus is not well resolved, but is commonly taken as evidence for a pause in subduction along the NE Asian margin. Our FT ages shed new light on this issue.

2.2. Ukelayat flysch

The Ukelayat flysch has a long history of geologic investigations (see review in Bogdonov et al., 1990). A regional synthesis has been thwarted by its monotonous lithology, great thickness, pervasive deformation, and relative inaccessibility. The unit is relatively well studied where it is structurally overlain by the Olyutorsky terrane. We observed the Ukelayat flysch at seven localities, mainly along the Olytorsky suture. The Ukelayet rocks are generally composed of medium- to thin-bedded, fine- to medium-grained sandstone and interbedded shale, locally with tuffaceous sandstone, siltstone, and conglomerate. Sandstones are compositionally uniform and are mainly quartzofeldspathic to subarkosic with minor volcanic fragments. Based on sandstone composition, paleocurrent directions, and geochemistry of shale, we suggest that the sediments of the Ukelayat were derived from a dissected continental arc and then dispersed in a forearc basin by axial currents parallel to the continental margin (Bullen, 1997; Sears 1996; Garver et al. 1998, Soloviev et al., 1998; Bogdanov et al., 1999).

Large olistostromes containing blocks of chert, basalt, and volcanic sandstone have been observed locally adjacent to the frontal part of the suture thrust (Bogdanov, 1988). The blocks appear to match lithologies in the overlying Olyutorsky terrane. The age of these olistostromal units is not well constrained, but a few fossil localities (foraminifera) suggest a Maestrictian to Paleogene age (Alekseyev, 1979).

2.3. Olyutorsky Arc

The Olyutorsky terrane represents an obducted Upper Cretaceous-early Tertiary island arc (Aleksandrov et al., 1980; Bogdanov et al., 1990; Stavsky et al., 1990; Worrall, 1991; Geist et al., 1994; Shapiro, 1995). The suture zone is represented by a spectacular thrust fault, variably called the Vatyna, Vyvenka, or Lesnovsk thrust that can be traced for some 500 km in central and northern Kamchatka. The thrust places the Olutorsky arc over a lower plate of deformed Ukelayet flysch.

The Olyutorsky arc contains three basic units (Aleksandrov et al., 1980; Grigoriev and Shapiro 1986; Alekseyev, 1987; Geist et al. 1994;). The basal unit is the *Vatyna complex*, which is dominated by pillow basalts, diabase sills, minor plutonic rocks and interlayered Aptian-Campanian cherts (Geist et al., 1994; Grigoriev and Shapiro, 1986). The overlying and interfingering *Achayvayam complex* is a Coniacian-Paleocene calc-alkaline volcanic series (Bogdanov et al., 1990; Worrall, 1991; Alekseyev, 1979). A Paleogene volcanic sequence, referred to as the *Govena Series*, includes tuff, basalt, and andesite, and a minor component of chert, siltstone, and shale (Geist et al., 1994; Bogdanov et al., 1990).

Fossils demonstrate that the Olyutorsky arc was coeval with the Okhotsk-Chukotka arc and the Ukelayat flysch. What distinguishes the Olyutorsky is its complete lack of terrigenous sediment. Thus, the suture boundary marks the collision of entirely unrelated oceanic and continental rocks.

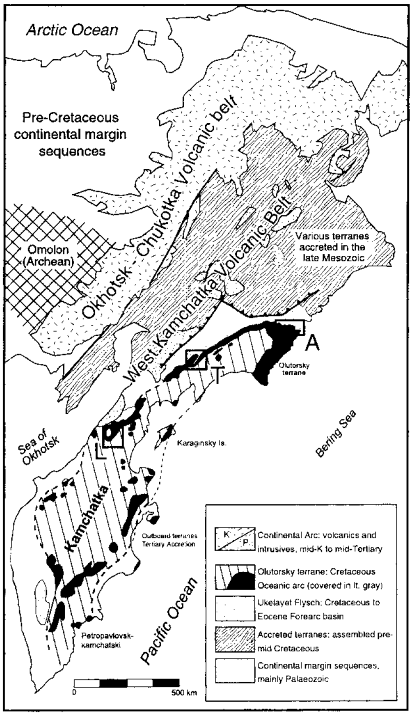

Fig. 2: Generalized geologic setting of the Koryak Highlands and the adjacent Okhotsk-Chukotka belt. Figure is modified from Tilman and Bogdanov, 1992 and Shapiro 1995.

3 FT Dating of Deterital Grains

We sampled the Ukelayat flysch and its stratigraphic equivalent (the Lesnovsk Group) in three areas over a distance of ~500 km in Kamchatka (see Figs. 1,2). Standard separation methods were used to isolate zircon from a crushed sample. The zircons were then dated using the external detector method (e.g., Garver, et al. 1999b). For each of the 27 samples dated, about 20 to 90 zircon grains were counted giving a total of about 1300 single-grain determinations (Figs. 3-5). Each FTGA distribution was deconvolved into a set of components (Brandon, 1992; Brandon and Vance, 1992), using the best-fit binomial peak-fitting routine of Galbraith and Green (1990). Calculations were done using the BINOMFIT program (Brandon, 1992, 1996; program is available at www.geology.yale.edu/~brandon). The F-ratio test was used to judge the maximum number of resolvable components present in each FTGA distribution (Brandon, 1992, 1996).

We have *a priori* information that the dated samples remained at cool temperatures after deposition. This conclusion is important for the interpretation of the zircon FT ages. Maximum temperatures should be <~200°C to ensure that zircon FT ages remain unreset (Brandon et al., 1998). The sampled Ukelayat shows only brittle deformation, with no evidence of pressure solution or cleavage formation. Secondary minerals are limited to minor chlorite, some illite after smectite, and albitization of plagioclase. Illite crystallinite was measured by M. Rahn (U. Freiburg) on <2 μm size fraction from 4 samples from our most northeastern study area. Techniques used are those recommended by Kisch (1991). Illite peak widths are reported using the Kübler index $\Delta 2\theta$ (standardized for a Cu K_α X-ray source). $\Delta 2\theta$ ranges from 0.70° to 0.80°, indicating very low grade (diagenesis zone; Kisch, 1987). $\Delta 2\theta$ decreases with increasing grade, with the transition from the diagenesis zone to the anchizone set at $\Delta 2\theta <$ 0.42° (Kisch, 1987). This transition is thought to occur at~200°C (p. 290 in Kisch, 1991), which indicates cooler maximum temperatures for the analyzed samples. This conclusion is consistent with FT dating of apatites from the dated zircon samples, which indicates that detrital apatites are also unreset and retain old ages that reflect cooling events in the source region (Garver et al., 1998; Soloviev et al, in press, Garver and Soloviev, unpublished). From these observations, we conclude that our samples remained well below 200° C after deposition and therefore the fission-track system has remained closed.

4 Interpretation

All samples show a wide range of grain ages, as expected for an unreset sandstone. Fig. 3 shows a typical FTGA distribution based on 90 zircons. Three components (or peaks) are present. As with most samples, P2 is the dominant component, containing 50% of the distribution; P1 and P3 are subordinate, making up 40 and 10%, respectively, of the distribution. FTGA components represent cooling events in the source, either related to near surface magmatic processes, tectonic exhumation, or erosion (Brandon and Vance, 1992; Garver et al., 1999a). We focus here first on the P1, which defines the minimum age for each distribution, and then on the older components.

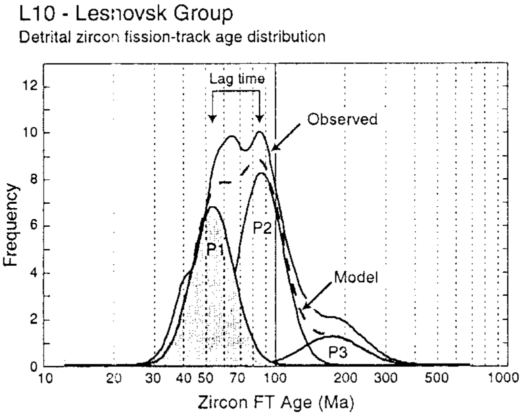

Fig. 3: Example of the distribution of detrital zircon in a typical sandstone sample (L10, from "L" in Figs. 1,2). Solid line is the observed distribution of all grain ages for the sample (90 grains total). Dotted line is the model distribution from the peak fitting results. Density plot constructed as recommended by Brandon (1996).

4.1. Minimum Ages

The P1 component appears to have been derived from active parts of a volcanic arc or rapidly exhumed rocks in the source area. Other studies have shown that the FT minimum ages can be used as a proxy for depositional age for sandstones derived from active volcanic sources (Brandon and Vance, 1992; Garver and Brandon 1994a,b; Carter et al., 1995; Garver et al., 1999a). P1 ages span the entire interval between ~88 to 44 Ma (Cenomanian-Campanian to Middle Eocene), suggesting over 40 Myr of continuous deposition (Fig. 4). These ages are remarkable given that the sampled units were mapped as Cretaceous.

The samples come entirely from the footwall of the Olyutorsky suture (Vatyna thrust and equivalents). In a strict sense, we can say that the suture must be younger sandstones, and the sandstones must be younger than the P1 ages. We suspect that there may be very little time separating these events. We have already noted that the P1 component was probably derived, at least in part, from a contemportaneous volcanic source. In turn, the Ukelayat flysch contains evidence of syncollisional deposition. In particular, we observed mass wasting deposits (olistostromes) containing slide blocks of volcanic rock derived from the overlying Olyutorsky terrane. Previous workers have recognized olistostromal deposits in the Ukelayat and have noted that these units appear to be found adjacent to the Olyutorsky suture. Our FT dating indicates Middle Eocene minimum ages for Ukelayat at the two locations where olistostromes were observed. ("A" and "L" Figure 2). In contrast, the Ukelayat that we sampled at a third location ("T" in Fig. 2) lack olistostromal deposits and also yielded older minimum ages (~55 to 88 Ma). The inference was that sampled Ukelayat there was deposited before collision started. We acknowledge that the olistostromal interpretation remains controversial; some workers prefer to interpret these block deposits as tectonic mélanges. Either way, we envision that tectonic intermixing might have occurred shortly after deposition, in order to account for the chaotic nature of these units. As such, our conclusion—that the youngest P1 ages, which are Middle Eocene, are nearly synchronous with the collision—would remain largely intact.

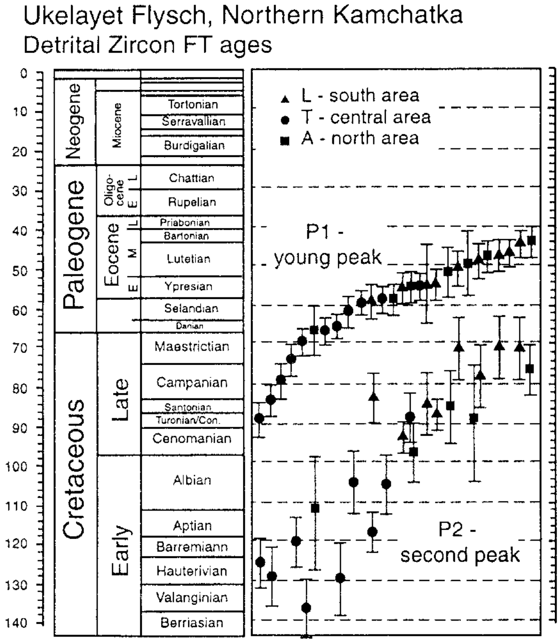

Fig. 4: P1 and P2 ages for samples dated for this study, arranged left to right, from youngest to oldest (± 1 SE).

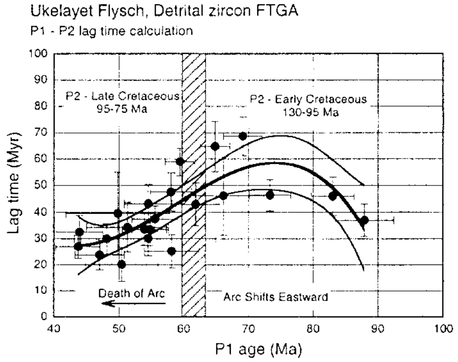

Fig. 5: Plot showing lag time for P2 as a function of depositional age. Depositional age is approximated using FT minimum ages (P1). The P2 inferred to represent exhumation of the basement of the Okhotsk-Chutkotka arc. Note the decrease in lag time after the inferred demise of the arc. This shorter lag time results from either faster exhumation or a falling geotherm.

4.2. Older Components

In addition to the P1 component, each FTGA distribution typically contains two or three older components. The ages and sizes of these older components vary from sample to sample. In general, one would expect an age peak from an exhuming source to remain the same or get younger with time (see Garver and Brandon, 1994b: Garver and others, 1999a). In our results, 22 of the 27 samples have a clearly defined P2, which is simply the next older peak. In almost all samples, P2 is composed of the greatest percentage of grains (~40-60%) and it ranges from ~70 to ~130 Ma. In almost every sample, P3 and P4 are defined by 20% or fewer grains. Assignment of these smaller peaks is difficult because there is reasonable probability that the peak might not be detected (Brandon, 1992).

The second population of zircon (P2) records the progressive exhumation of the metaplutonic basement of the Okhotsk-Chutkotka arc. P2 consists of a mid- to Late Cretaceous peak defined by ~40-60% of the grains in each sample. This inferred source is based on two important observations. First, sediment composition and geochemistry requires that the Ukelayat flysch has a source with high-grade metamorphic rocks that persisted in the source terrane for tens of millions of years (Bogdanov et al., 1999). Second, the only deeply exhumed candidate source in this part of the Russian Far East lies in the core of the Okhotsk Belt where mid-crustal rocks are exposed (Nokleberg et al., 1998).

P2 is clearly a *forward-moving peak* that can be ascribed to the progressive exhumation of rocks in the source area (Garver et al., 1999a). Provided the FT depositional age is a reasonable proxy for age of deposition, then rates of exhumation can be estimated from each sample (Figs. 4,5,6). The difference between FT depositional age and P2 (i.e. peak "lag time") is between ~30 and 70 Myr. This lag time represents the time required for rocks to pass through the FT closure for zircon and then reach the surface. With typical continental geothermal gradients (~25-30°C/km), this lag time results in exhumation rates of about 200 to 400 m/Myr (see Garver et al., 1999a). These rates are not unusually high, but given 44 Myr we can assume that between about 9 and 18 km of crustal material was removed from this area. This amount of exhumation would be sufficient to expose amphibolites and other high-grade metamorphic rocks characteristic of parts of the Okhotsk belt. Note that the Coast Plutonic Complex, also in the northern Pacific Rim (in BC, Canada) is about the same age and had a similar history (Garver and Brandon, 1994b; Garver et al., 1999a).

Does the lag time and changes of lag time with depositional age indicate how exhumation may have proceeded with time? One trend in the data is that in the older samples (> ~58 Ma), lag time is longer as compared to the younger samples (Fig. 6). This reduction in lag time suggests exhumation rates increased (here about doubling from ~200 m/Myr to ~400 m/Myr). Another explanation is that geothermal gradients changed and as a result paleo-isotherms in the crustal section became closer assuming exhumation rates remained more or less constant. Either way, these data indicate an important change in the evolution of the source region at about 60 Ma. We suggest this change is related to the demise of the Okhotsk Arc.

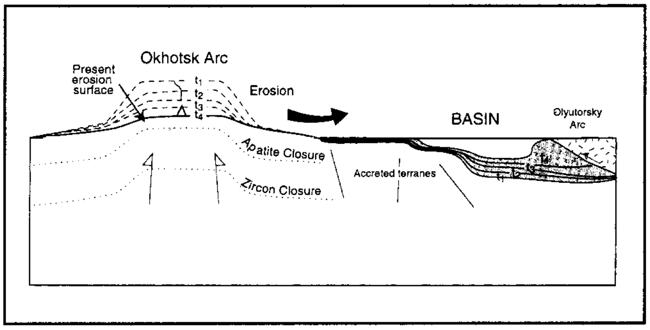

Fig. 6: Simple cartoon showing the inferred setting of the Ulkelayet basin with sediments derived from an eroding continental arc. At the time of collision, the Ukelayet basin changed from a forearc basin to a foreland basin to the Olyutorsky collision zone (shown to the right).

5 Conclusions

This study shows the utility of using detrital fission track thermochrometry for constraining depositional ages of arc-derived sediments. Although the sediments are derived from an active continental arc, young volcanic zircons comprise a minor component of the observed zircon population. However, by isolating this young component, we are able to track the age of volcanic activity in the source. Our data refute the idea of a hiatus in arc volcanism along the Asian margin at the end of the Cretaceous. Instead, we show a continuous supply of volcanic zircon from mid-Cretaceous to Eocene. Our data do not indicate the location of the arc, but a change in exhumation rates at 60 Ma (discussed above) is consistent with the eastward shift from the Okhotsk-Chukota arc to the Koryak-Western Kamchatka arc.

Older grain ages indicate prolonged deep erosion of the Okhotsk-Chukota arc, which suggests that stood topographically high as an "Andean-style" arc for some tens of millions of years. This progressive exhumation brought rock upwards through the main spine of the arc. The result was that the last stage of volcanism was locally build on mid-crustal rocks, much like the modern Cascadia arc in western Washington State. The Cascade Arc was eroded down to mid-crustal levels during evolution of the arc and the High Cascade volcanoes such as Glacier Peak , Mt. Baker, and Gribaldi, built over the last 5 Myr., sit directly on crystalline basement rocks. Factors that contribute to a topographically high arc include thermal buoyancy, crustal thickening by magmatic accretion of mantle-derived melts, and orogenic shortening. In the case of the Okhotsk-Chukotka arc, erosional exhumation was slow, at rates of 200 to 400 m/Myr. Similar rates have been recognized in the Coast Plutonic Complex of western British Columbia, which represents an extinct northern continuation of the Cascade volcanic arc (Garver and Brandon, 1994b).

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