Verkhoyansk Project

Final Report

by

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INTRODUCTION

The Verkhoyansk fold and thrust belt of eastern Siberia forms an 2000-km long, and up to 500 km wide, zone of continental shortening extending from the Laptev Sea in the north to the Sea of Okhotsk in the south (Fig. 1). This orogen has similar proportions to the portion of the North American Cordillera from the Canadian border to Alaska. The Verkhoyansk fold and thrust belt involves Late Precambrian to Jurassic shelf to basinal strata deposited along the eastern paleo-Pacific margin of the North Asia craton as well as Cretaceous deposits of the Pri-Verkhoyansk foreland basin. This margin developed as a consequence of rifting in the Late Precambrian and was followed by renewed rifting/subsidence events in the Late Devonian to early Mississippian which lead to the deposition of up to 7 km of continental margin strata in the thickest part. Shortening in the fold and thrust belt began in the Latest Jurassic to Early Cretaceous and continued until E. Paleocene. This deformation was accompanied by metamorphism in the internal parts of the belt, and the emplacement of high-level granitic plutons. Deformation in the West Verkhoyansk was probably linked to accretion of island arc sequences of the Kolyma-Omolon superterrane to the margin of the North Asia craton and in the South Verkhoyansk to collision of the Okhotsk terrane. In addition, in the South Verkhoyansk there is evidence for Early Tertiary denudation possibly related to strike-slip deformation associated with the opening of the Sea of Okhotsk.

Goals of the Project

We undertook this research project to better understand the structural, stratigraphic, and thermochronologic history of the Verkhoyansk fold-and-thrust belt and to relate its evolution to that of the Russian Far East. Obviously given the magnitude of the Verkhoyansk orogenic system we could only study limited areas in the field. We concentrated on two transects, 150 to 200 km long, extending from the foreland to the internal part of the fold-and-thrust-belt. The first transect was located in the southern Verkhoyansk at about 61°N latitude. The second transect was located north of the bend at about 65°N latitude in what is known as the West Verkhoyansk (Figs. 1 and 3). Even though these transects are located more than 400 km apart we can effectively relate them to each other and draw significant conclusions about the overall evolution of the belt thanks to the extensive geological research previously carried out by Russian geologists from the Diamond and Precious Metal Geology Institute (former Institute of Geological Sciences) of the Siberian
Branch of the Russian Academy of Sciences, and from the Yakutian Geological Survey with whom we collaborated.

**Accomplishments**

In spite of all the logistical difficulties we were able to successfully carry out both transects across the Verkhoyansk. In the field we collected abundant structural data, made first-order stratigraphic observations, and collected samples for petrographic study, for apatite fission track dating, for $^{40}\text{Ar}/^{39}\text{Ar}$ dating of igneous and metamorphic rocks and for U-Pb dating of plutonic rocks. We also collected samples to establish the

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**Figure 1.** Digital elevation model of northeast Asia showing the location of the Verkhoyansk fold-and-thrust belt and the location of the two transects carried out for this project. GTOPO30 DEM.
thermal maturity through vitrinite reflectance measurements of coal-bearing rocks and our Russian colleagues collected carbonate rocks for paleontological identification and determination of conodont alteration indices. We have processed and carried out the analytical work on most of the samples from the Southern transect and we present the data below. In addition, through our collaboration with the Diamond and Precious Metal Geology Institute of Yakutia we have assembled a more regional data base of geological and thermal maturity data which is the product of many years of Russian research which we will forward at a later date.

Preliminary results from this research have been presented in poster form at the American Geophysical Union National Meeting in San Francisco, in December 2000 (Toro et al. 2000), and as an oral presentation at the Geological Society of America national meeting in Boston in November 2001 (Toro et al. 2001). Abstracts from these two presentations can be found in Appendix 1. A Powerpoint presentation for the GSA talk can be viewed at:


Remaining Work

We had great difficulty exporting samples for thermochronological work from Yakutia through the Russian customs system and this greatly delayed the analytical work which is at the core of this project. For example, it took nine months to receive the samples from the second (northern) transect in the USA. After additional difficulties carrying out the mineral separations, the samples were only sent to irradiation in early 2002, and we don’t expect to have the analytical work completed until the second semester of 2002. For this reason this report focuses on the southern transect where we have a more complete data set. We will forward an update to this report making comparisons between the two transects once we have completed the fission track analyses.

Based on data collected for this study we plan to publish a journal article on the South Verkhoyansk, one on the metamorphic rocks of the Upper Maya region of the Okhotsk block, and one article comparing the timing of deformation and structural style of the north and south Verkhoyansk. We will forward pre-prints of these articles to Exxon Mobil as soon as they are completed.

Regional Structure of the Verkhoyansk

On the basis of variations on structural style, stratigraphy, and morphology of the orogen, it has been divided into three main sectors (Parfenov and Prokopiev, 1995). These are, from north to south, the Olenek, West
Verkhoyansk, and South Verkhoyansk sectors (Fig. 2). The Olenek sector has east-west structural trend parallel to the Laptev sea margin. The deformation in this sector is moderate, expressed mostly as broad anticlines with few thrust faults breaching the surface. Based on sparse wells and gravity data, Late Proterozoic sedimentary rocks are believed to be involved in the core of the folds.

The West Verkhoyansk sector includes the main north-south trending portion of the orogen as well as the orocline bend that is so characteristic of the Verkhoyansk. A deep and narrow foreland basin filled with syn-tectonic Cretaceous clastic deposits exists along this sector of the Verkhoyansk.

The West Verkhoyansk has been subdivided into four segments. Our northern transect is located on the Kuranakh segment at the broadest portion of the fold-and-thrust belt, north of the bend (Fig. 3). In this area Carboniferous to Cretaceous, predominantly clastic, rocks are involved in a series of long, linear folds. Only in the frontal portion do west-vergent thrust faults breach the surface. The structure of this segment is described in more detail below in the context of our northern transect. In the Baraya segment the structural trend turns east-west. On the basis of the en echelon arrangement of folds, as well as field observations, it has been inferred that this portion of the belt formed with a significant left-lateral component (Zoneshain, 1965).

Along the South Verkhoyansk sector the trend of the structure returns to a north-south trend and the structural style is quite different from areas to the north. There are no foreland basin deposits preserved in front of the South Verkhoyansk, and the structure is dominated by a series of thrust sheets involving Late Proterozoic to Jurassic rocks. Towards the hinterland the rocks become progressively younger, metamorphic grade increases, and structures are east-vergent. There is a belt of low greenschist grade metamorphic rocks in the hinterland of the South Verkhoyansk intruded by several large granodioritic plutons of Early Cretaceous
age. In contrast, only a few small granitic plugs are present in the Kuranakh segment of the West Verkhoyansk.

Figure 3. Regional structural map of the Verkhoyansk fold-and-thrust belt showing the location of the transects carried out for this study.
As stated in the introduction, the Mesozoic Verkhoyansk fold-and-thrust belt was preceded by successive rift events which affected the margin of the North Asia craton. During the Late Proterozoic more

Figure 4. Structural map on top of crystalline basement (after Yu. Kh. Protopopov).

successive rift events which affected the margin of the North Asia craton. During the Late Proterozoic more
than 3.5 km of continental margin clastic and carbonate strata were deposited in the Aldan-Maya basin located adjacent to the south Verkhoyansk segment (Fig. 4). These Late Proterozoic strata are involved in the frontal thrust sheets of the south Verkhoyansk and exert important control on the structural geometry.

The Vilyui basin, a Middle Paleozoic failed rift, trends NE-SW across the eastern Siberian platform. This basin is filled with up to 6 km of red beds and basalts mostly of Late Devonian to Early Carboniferous age. Extensive swarms of basaltic dike of the same age intruded the Siberian platform. Evidence for this rift event is also found in the South Verkhoyansk sector where there are numerous north-south trending Devonian dikes, and small outcrops of the rift-related sedimentary sequence.

The fact that the Vilyui rift arm intersects the Verkhoyansk at the location where it bends from a northerly to an easterly trend strongly suggests that the shape of the orogen was controlled by the shape of the continental margin that was created after the Middle Paleozoic rift event (Fig. 4).

FIELD TRANSECTS

Southern Transect

Logistics

During the summer of 1999 Elizabeth Miller and Jaime Toro carried out five weeks of field work in collaboration with Andrei Prokopiev and Valodia Tarabukin from the Institute of Geological Sciences of Yakutia (now called Diamond and Precious Metal Geology Institute). We traveled by small plane to the village of Eldikan located on the Aldan River (Figure 5) where all the necessary food and supplies for this expedition had been stored the previous spring before break-up of the Aldan River. This area was chosen for the first transect because the fold-and-thrust belt is accessible via a good dirt road that connects Eldikan to gold mines located on the upper reaches of the Allakh-Yun’ River and on the drainage of the Yudama River. The primary means of transport was a 6x6 Saigak diesel truck rented form the local gold mining company. Our routes are shown in white on Fig. 5. In addition we worked on foot for five days in the Tarbagannakh range, located east of the village of Allakh-Yun’, in order to examine the metamorphic rocks which are exposed in the internal portion of the belt, as well as the syn-tectonic Tarbagannakh granite. We reached the village of Yugarionok, the southernmost point in the area we visited, by hiring a small jeep on the East bank of the Allakh-Yun’ River which we could not cross with our truck. In Yugarionok we rented a motor boat and
Figure 5. Simplified geological map of part of the South Verkhoyansk studied during the southern transect. See Fig. 3 for location. Most sample numbers have the prefix 99JT. Tar is the Tarbagannakh pluton, Uem is the Uemliakh pluton.
traveled 30 km to the east along the Yudama River. The goal of that branch of our transect was to study reported metamorphic isograds within the Carboniferous slate belt and to determine if it is feasible to access the contact between the Verkhoyansk fold-and-thrust belt and the Okhotsk terrane. However, we found this to be very difficult since no track-vehicles are available at the gold mines on the Yudama. The final leg of the southern transect constituted a second crossing of the frontal thrust sheets along the Allakh-Yun’ River on rubber boats. This afforded the opportunity to study excellent exposures of the Cambrian and Late Proterozoic stratigraphic sections in along the river banks, as well as limited exposures of the Jurassic cover, and to make comparisons with our initial crossing along the road as much as 75 km to the north.

Data Collected

Given the size of the field area, and the time available for field work, we could not carry out detailed field mapping, instead we made traverses on foot of key well-exposed sections, and spot checks in other areas in order to examine all the principal lithologic units that characterize each structural domain within the thrust belt. We had Russian geological maps of covering most of our transects at 1:200,000 scale (Ferdman et al. 1963; Losev et al. 1970; Starnikov, 1983; Yan-Shin-Tshin, 1971), as well as a compilation map of the whole area at scale 1:500,000 which served as the base for Fig. 5(Nushkar’ et al. 1995). We found these maps to be generally accurate in the regions of simpler structure such as the frontal thrust sheets of the Kyllakh Zone (discussed below), but were more problematic in regions where deformation is more intense. In particular within the slates and phyllites of the Sette-Daban and Allakh-Yun’ Zones what was often mapped as bedding is in effect a transposed metamorphic cleavage, therefore the stratigraphic thicknesses reported in the maps are incorrect. It is important to note that Soviet map-making regulations required that 1:50,000 scale geologic maps break down formations or map units into units that are 500 m or less in thickness. These regulations led to the arbitrary division of existing map units in many places, replacing old formation names by multiple new formation names. In many cases this was unwarranted, and the older (more generalized) stratigraphic and formation names are still the most appropriate given the overall detail of mapping and geologic knowledge of the region.

In addition to evaluating existing maps and stratigraphic section descriptions, we focused on structural measurement for cross-section construction, and making observations to determine the degree and
style of deformation of the rocks in various parts of the thrust belt. We looked closely at metamorphic grade, the relationship of metamorphism to structural fabric development, and, finally, the relation of both metamorphism and structural fabric development to the emplacement of igneous intrusions and associated mineralization.

We also collected representative samples of all major units to characterize the lithologies, sampled arenites and granitic rocks for apatite fission-track dating, and sampled the low-grade metamorphic rocks for $^{40}\text{Ar}^{39}\text{Ar}$ dating from the area surrounding the Tarbagannakh pluton. The goal of the thermochronologic sampling was to constrain the timing of the development of the Verkhoyansk fold-and-thrust belt. Finally we collected samples for vitrinite reflectance determination from coaly plant material in the Jurassic sandstones of the frontal thrusts and the foreland. The results of our analyses are discussed below.

**SOUTH VERKHOYANSK**

The southern part of the Verkhoyansk belt differs from its counterpart to the north in that it is narrower, and structures within it are generally steeper, particularly in the interior part of the belt. From west to east, the belt can be divided into the following structural or tectonic zone (Fig. 8):

1. Flat-lying strata of the *Siberian Platform*
2. The *Kyllakh Zone* of broadly-spaced folds and thrust faults that involve Precambrian to Jurassic age strata
3. More highly deformed and slightly metamorphosed, mostly lower Paleozoic strata of the *Sette-Daban Zone*
4. Deformed and weakly metamorphosed, primarily Carboniferous to Permian basinal strata of the *Allakh-Yun’ Zone*, intruded by Cretaceous plutons
5. The more platformal (?) sequences of the *Okhotsk Terrane*, which was not investigated during this study.

**Stratigraphy**
Representative stratigraphic columns from the Kyllakh and Sette Daban zones are shown in Figures 6 and 7 as summarized from (Ferdman et al., 1963; Losev et al., 1970; Starnikov, 1983; Yan-Shin-Tshin, 1971). The description of the rocks below are modified by our observations and field notes compiled the summer of 1999.

Important distinctions characterize the above named zones or successions. Depositional basement is not exposed in the southern Verkhoyansk, but a 3.5 km thick section of Late Precambrian (Riphean) strata intruded by numerous gabbro sills are exposed together with overlying Vendian, Cambrian and Ordovician units. The Cambro-Ordovician section of the Kyllakh Zone was deposited in a slope to shelf basin setting and is less than 1 km thick. In contrast, the Sette-Daban Zone exposes a great thickness of basinal facies of carbonates of Cambrian, Ordovician and Silurian age overlain by shelf facies Devonian limestones. True stratigraphic thicknesses are uncertain due to the deformation of the rocks. The Early Paleozoic succession is overlain by Lower Carboniferous conglomerate and red beds that grade up into more basinal clastics of the Permo-Carboniferous Verkhoyansk terrigenous complex. This upper part of the section is thin, and preserved mostly as inliers in the cores of synclines. The Allakh-Yun’ Zone exposes thick and monotonous almost basinal sections of Permo-Carboniferous clastic turbidites and graphitic shales.

These successions can be interpreted as a Late Precambrian to Devonian continental margin sequence which ranges from platform facies in the western part of the transect to more basinal facies to the east, overlain by a latest Devonian to early Carboniferous rift sequence, which was in turn followed by a period important subsidence and deposition of thick continental margin clastic deposits. Evidence from the eastern part of the Verkhoyansk fold belt, outside of our study area, suggests that subsidence and clastic deposition continued into the Triassic.

**Siberian Platform:**

The western part of our transect began in flat-lying rocks of the Siberian Platform. Basement is presumably Archean and Early Proterozoic igneous and metamorphic rocks of the Aldan Shield, although these are not exposed in the area. Shallow-water marine deposits of Late Proterozoic (Riphean) to Early Paleozoic age covered most of the shield (Zonenshain, 1990). A depocenter existed in front of the south Verkhoyansk that is known as the Maya basin. Here Riphean deposits attained more than 3.5 km in thickness. These rocks are exposed in the Kyllakh segment of the Verkhoyansk and are described below. The Maya
Yudama Group. Dolomite, limestone, marl, argilite, and tuffs.

Ust’kirbyn Group. Siltstone, brown argilite, and sandstone.

Kandik Fm. Massive white quartz sandstone, conglomerate, and siltstone. Gabbro and basalt sills.

Maya Group. Massive limestone, stromatolitic limestone, dolomite, calcareous shales and massive quartz sandstone.

Figure 6. Stratigraphic columns of rocks of the Kyllakh zone of the South Verkhoyansk (after Prokopiev et al., 1999).

basin may represent a Late Precambrian failed rift as evidenced by the presence of abundant gabbro sills that intrude the section. Vendian and Cambrian shallow marine carbonates overlie the Riphean deposits. These are unconformably overlain by thin Early Jurassic arkosic fluvial sandstones probably sourced from the craton. This is supported by the presence of abundant detrital muscovite. It appears that though out the Paleozoic and early Mesozoic the Siberian platform was a relatively stable high-standing area. Evidence for late Devonian to early Carboniferous rifting is only seen to the north in the Vilnuy basin and to the east in the Sette-Daban zone of the south Verkhoyansk.

**Kyllakh Zone:**

**Late Proterozoic:** The oldest rocks exposed along our transect are thick and resistant Middle Riphean
limestones and dolomites of the Maya Group (Figure 6). These units are consistently exposed at the base of each of the three frontal thrust sheets indicating that the basal detachment lies at the base of the Middle Riphean carbonates. The presence of stromatolites in the Middle Riphean dolomites indicates deposition in a shallow water platformal environment.

The Maya Group carbonates are overlain by a succession of Late Riphean, dominantly clastic rocks which include distinctive clean white sandstones of the Kandik Formation probably near shore blanket sandstones. Although the rocks of the Kyllakh zone are unmetamorphosed, the sandstones of the Kandik Formation appear to be completely quartz-cemented to the point that in the field they have the appearance of orthoquartzites. The upper part of the Riphean succession is composed of alternating thin-
SETTE - DABAN RIFT
AND POST RIFT SEQUENCES

Basal portion of the Verkhoyansk terrigenous complex. Dominantly pyritic graphitic slates and phyllites, dark dirty sandstones (quartzites), siltstones, shale clast conglomerates and minor conglomerates with granitic, gneissic and volcanic clasts. Interpreted as a sequence of turbidites.

Post-rift marine carbonates having increasingly deeper water facies upward.

Sequence beginning with quartz pebble conglomerate and red beds of probable continental origin followed by limestone boulder conglomerate and shallow marine fossiliferous carbonates.

Section dominated by shallow water fossiliferous limestones and dolomites intercalated with basalts. The Givetian Zagadoshnaya Formation consists of thick and thin-bedded gray limestone with giant brachiopods and tabular corals.

**Fig. 7 cont.** Stratigraphic columns of Middle Paleozoic rocks of the Sette-Daba zone of the South Verkhoyansk (Prokopiev et al., 1999). Symbols are as in Fig. 6.

Formations:
bedded, brown siltstones and argillites. The Riphean section is intruded by numerous hornblende-bearing
gabbro and basalt sills, some of which are very thick. The sills appear to be essentially conformable with the
stratigraphy. We did not observe any evidence of extrusive volcanism. The Riphean units have a stratigraphic
thickness of about 2.5 to 3 km in this area.

Vendian: The Vendian is characterized by white dolomites, stromatolitic limestones, argillites and sugary
quartzites. The Riphean/Vendian contact is beautifully exposed on the second thrust sheet where it consists of
a sharp transition from clastics to white thick-bedded, but laminated dolomite. There is a basal layer of gritty
dolomite with coarse quartz grains.

Cambrian: In the frontal thrust sheets the Cambrian consists of typically thin bedded limestones and marls.
Fossils (except for conodonts) are rare and very few sedimentary structures other than laminations exist. Our
interpretation is that this sequence represents a shelf basin succession. Its thickness and stratigraphy is
difficult to ascertain on account of deformation. From our observations and structural data collection, the
Cambro-Ordovician of the Sette Daban Zone appears to be involved in kilometric-scale, steep-limbed folds.
Bedding/cleavage relationships indicate that the rocks are everywhere strained but are rarely obviously folded
on the outcrop scale. Thick panels of upright versus overturned sections occur as deduced by bedding
attitudes and the location of stratigraphic contacts with younger overlying rocks.

Middle Ordovician: The Middle Ordovician (Labystakh Fm.) consisted of thin to medium bedded limestone
turbidites with well preserved sedimentary structures. The base of the unit was dominantly greenish
calcareous phyllite with orange siderite clumps not unlike the Cambro-Ordovician rocks described above.
However, overall the Middle Ordovician is reported to be a more limestone-rich section.

Silurian: Where observed, the Silurian (Oron Fm.) consisted of mostly light grey to medium grey shallow-
water dolomite with sedimentary structures indicating lagoonal to tidal flat environments of deposition.
Some silty and shaley units occur in the sequence, but for the most part, it is a more resistant, ridge-forming
dolomite.

Devonian: The Devonian of the Sette Daban Zone everywhere unconformably overlies the Silurian.
Devonian rocks are preserved only locally in the cores of synclines. Because the Devonian and Early
Carboniferous represent the transition from stable platformal to a rift environment, their stratigraphy is
complicated and a plethora of formation names are found on the Russian maps. Regionally, the Lower
Devonian is mostly shale with dolomite and conglomerate horizons, overlain by a distinctive, ridge-forming, highly fossiliferous mid-Devonian (Givetian) limestone (Zagadoshnaya Fm.). The limestone is brown to grey, medium to thick bedded and alternates with thin-bedded to platy dark grey to light grey limestone. Giant brachiopods and tabular corals are conspicuously present in the unit wherever we observed it. This platformal sequence is overlain by a section which is comprised of shalier limestone, calcareous shale and shale and presumably deposited in deeper water. It is reported that basaltic volcanics are found in the Middle Devonian section, although we did not observe these.

Lower Carboniferous: The lower Carboniferous is a conspicuous ridge-forming unit that contains very distinctive lithologies (Khamamuy Fm.). According to the literature, the unit varies considerably in thickness and facies but where we studied it, it was comprised of a consistent set of lithologies. Basal units are reddish colored, cross-bedded sandstones, grits and conglomerate of possible
continental origin that grade upsection into massive carbonate-clast conglomerate (clasts of Ordovician and Devonian age carbonate are represented according to existing conodont data (V. Tarabukin pers. com., 1999)) deposited in a marine setting based on interbedded calc-arenite with abundant fossils. Fossils are mostly crynoid stems and the highly fossiliferous rocks are mostly of lower Tourneasan age (Early Mississipian). These conglomerates and calc-arenites are in turn transitional upwards to medium-bedded grey limestone that becomes siltier and shalier upsection and ultimately transitional into a dominantly black siltstone succession. We interpret the lower Carboniferous as representing a rift assemblage which preceded rapid subsidence and deposition of the Carboniferous Verkhoyankes clastic wedge best exposed in the Allakh Yun’ zone.

Allakh-Yun’ Zone

Permo-Carboniferous: Permo-Carboniferous sections as much as 3-4 km thick are reported from the Allakh-Yun’ Zone and referred to as the Verkhoyansk terrigenous complex. These strata are dominantly marine clastics, mostly consisting of shale, siltstone and lesser fine-grained sandstone, with occasional thick more resistant sections of coarser sandstone and pebble conglomerate. Today the entire section is metamorphosed to low greenschist grade and is characterized by graphitic slates and fine grain dark quartzites. We interpret most of the section to represent distal turbidites alternating with massive mud- and silt-rich sections with little or no preserved sedimentary structures. The muds and silts are dark grey to black, organic-rich, with pyrite throughout. Sandstones are medium to fine grained and vary in abundance depending on the location. The sandstones occur mostly as graded beds and/or massive grain-flow deposits, often with spectacular horizons of black shale rip-up clasts. Along the Yudama River in the southernmost part of our transect where conglomerates in the section were coarse enough, we identified clasts of dark siliceous argillite, perhaps derived from older parts of the underlying sections, rarer gneissic to felsic granitic clasts, some mafic and felsic volcanic clasts, and rare clasts of fossiliferous limestone.

Given the monotonous nature of the Permo-Carboniferous section, its metamorphic grade, its degree of deformation, its lack of distinctive marker horizons and paucity of fossils, it was our impression that it is difficult to tell where you are in the stratigraphic section and thus distinguish the Permian part of the section from the Carboniferous or identify the individual formations that are shown on the Russian maps. In discussion with Russian geologists, it appears that the base of the Permian is thought to be marked by a tillite related to Gondwanaland glaciation. Our opinion is that this purported distinction represents somewhat
wishful thinking, and that really, there is no simple way of clearly dividing the stratigraphy of this thick monotonous clastic section. Some of the geologic maps we worked with showed only sandstone versus shale lithologic designations without assigning a specific age. This appeared to be a more reasonable approach to mapping structures within the section. Determination of the thickness and exact stratigraphy of the Permo-Carboniferous is compromised by the lack of detail known about its stratigraphy as well as by the intensity of deformation. In several places it was apparent to us that what the Russian maps (e.g. Losev, 1970) portrayed as bedding attitudes was actually a metamorphic cleavage thus the thickness of measured sections is probably mistaken.

**Structure and Metamorphism**

The structure of the southern Verkhoyansk fold-and-thrust belt appears to be relatively simple and consistent across large distances along strike. At the latitude of our transect there are a set of four frontal thrust sheets (Kyllakh zone), followed by a more internal zone of relatively upright folding and incipient metamorphism (Sette-Daban zone), in turn followed by a large area of low grade rocks with consistently west-dipping cleavage, indicative of east-vergent deformation (Allakh-Yun’ zone). Syn-to late-tectonic (Early Cretaceous) granitic plutons intrude the core of the range.

Overall the strata become younger towards the interior of the belt (Late Proterozoic in the frontal part, Permian in the core) even though metamorphic grade increases towards the core of the range. This pattern is the result of the fact that the Paleozoic stratigraphic wedge involved in the deformation thickens considerably to the east. There is a clear link between the structural style and the stratigraphic characteristics of each one of the zones described above. We interpret this as

![Figure 9](image-url)
resulting of an underlying structural control to the Paleozoic depositional patterns and to inversion of this structures during the subsequent development of the Mesozoic fold-and-thrust belt. Thus the transition from the Kyllakh to the Sette-Daben zone probably corresponds to the inversion of the hinge zone separating shelfal from slope and basinal strata, probably in turn controlled by a basin-bounding normal fault system of Late Devonian to Early Mississippian age.

**Kyllakh Zone:** The frontal part of the Verkhoyansk is a classic west-vergent thrust belt with a basal detachment at the base of thick and rheologically strong Middle Riphean carbonates. Four main thrust sheets about 5 km thick and regularly spaced ~15 km apart define the main structure. Internal strain within each thrust sheet is moderate, although the thin bedded Early Paleozoic units (typically the Cambrian Ust-Maya Fm.) are folded in outcrop scale, west vergent folds. Shortening is moderate: restoration of the four frontal thrusts yields 18 km of displacement or 70% shortening. Three of the four frontal thrust faults die-out to the north of the location of the cross-section shown on Plate 2 with a distance of less than 65 km (Plate 1). The shortening appears to be transferred to a single frontal fault that produces a salient in the belt (Fig. 1).

**Sette Daban Zone:**

In the transition between the Kyllakh and the Sette Daban zones metamorphic cleavage is progressively better developed. Typically the rocks within the Sette Daban zone display a steeply dipping axial planar cleavage which indicates that the section is involved in large upright folds. Shaley units have phyllitic textures and are sometimes transposed so that the dominant layering is the cleavage, not the bedding. The internal strain is accommodated within the more massive carbonates by spaced

![Figure 10. Stereonet plot of poles to cleavage in the Sette Daban zone. Cleavage dips predominantly to the ESE indicating that the deformation was East-vergent in the structural fan of the Sette Daban.](image-url)
pressure-solution cleavage. The strike of cleavage is remarkably consistent, typically about 020 ± 5°. The attitude of cleavage varies from east dipping in the western part of the Sette-Daban zone to northwest dipping in the eastern part as well as throughout the Allakh-Yun’ zone. This means that the Sette Daban zone is a structural fan where the deformation changed from west vergence to east vergence (Plate 2). We interpret this change in the vergence of structures as a result of the inversion of the deep and Late Paleozoic basin strata of the Verkhoyansk continental margin.

Through most of the Sette Daban and the Allakh-Yun’ zones there is only one metamorphic fabric developed (S\textsubscript{1}). Therefore the deformational history appears to have been rather simple and consistent in this area. In only one area in the central part of the map area (location 52,65; Fig 5) did we observe a weakly developed second cleavage expressed as kink bands which refolded S\textsubscript{1}. This location is very close to the Burkhalala strike slip fault which may be responsible for this additional deformation. Except for this weakly developed S\textsubscript{2} fabric, we did not see any evidence of significant post D\textsubscript{1} deformation.

Allakh-Yun’ Domain: Bedding/cleavage

**Figure 11.** Stereonet plot of poles to slatey/phyllicit cleavage in the Allakh Yun’ zone. The consistent ENE dip of the plane of flattening indicates east-vergent deformation. The fold axis is consistent with that of the Kyllakh and Sette Daban zones demonstrating that the deformation was coaxial.

Due to the monotonous nature of the stratigraphy it is very difficult to map individual faults, but it is likely...
that east-vergent thrust faults exist throughout. The Permo-Carboniferous rocks are usually cut by several sets of quartz veins which host the gold mineralization, and are further evidence of the strain that occurred during development of the fold-and-thrust belt.

The Russian literature (Andriyanov, 1973) describes a post-tectonic metamorphic belt of staurolite grade rocks in the central part of the Allakh-Yun’ zone. We failed to find evidence for this metamorphic belt. The grade of metamorphism is amazingly consistent throughout and remains in the low greenschist facies with the exception of contacts of the granitic batholiths of the central Allakh-Yun’ zone. In the vicinity of the Tarbagganakh batholith we found fine chloritoid, staurolite, and biotite. The textural relationships indicate that mineral growth was at least in part synchronous with development of the metamorphic fabric. Therefore we believe that intrusion of the granites took place during the waning stages of ductile deformation in the Allakh Yun’ zone.

Geochronology

40Ar/39Ar Data

In order to constrain the timing of metamorphism, ductile deformation, and plutonism within the Allakh-Yun’ domain of the South Verkhoyansk, we carried out 40Ar/39Ar analysis of mineral separates from six samples (see Appendix 2 for the complete analytical data, Table 1 for summary data, Fig. 13 for the spectra, and Fig. 5 for sample locations). The samples were analyzed at the Stanford geochronology laboratory using procedures similar to those described by Hacker and Wang (1995).

The oldest age comes from sample 99JT65, collected from the eastern margin of the Sette Daban zone on the bank of the Allakh Yun’ River (Fig. 12 A). This sample was white mica separated form a calcareous phyllite of the Ordovician Labystakh Formation. It yielded a spectrum with a low temperature portion with ages ranging between 92 and 122 Ma representing 28% of the released 39Ar, and a high temperature portion of progressively older ages between 144 and 161 Ma. This pattern suggest that the sample represents a two-component mix, and the ages cannot be interpreted directly. It is possible that in addition to newly crystallized mica of Early Cretaceous age, this rock incorporated a minor component of Paleozoic detrital mica thus yielding anomalously old ages. Sample 99JT52, collected from the same unit only yielded a cleaner (albeit non-ideal) spectrum. The weighted mean plateau age for this sample was 128 ± 0.3 Ma (Hauterivian), although individual temperature steps within this plateau range from 124 to 136 Ma. Because the Ar closure temperature of white mica (~350°C) is greater than the maximum paleotemperature experienced by these fine grain low-greenschist grade phyllites, we believe that this age approximates the timing of cleavage
development and recrystallization of the Ordovician rocks. This age is 7 Ma older than the ages from the plutons in the core of the South Verkhoyansk (discussed below). It provides a minimum constrain for peak deformation in the South Verkhoyansk.

We analyzed biotites from the Tarbagannagh Pluton, located on the east bank of the Allakh Yun’ rive, at the northernmost point of our the area we visited, and from the Uemliakh Pluton which is the largest granitic body in the entire Verkhoyansk belt. Both granites yielded reliable and statistically undistinguishable 40Ar/39Ar ages of about 120 ± 1 Ma (Fig. 12 C). Although these can only be interpreted as dating cooling through the closure temperature of biotite (~300°C), they approximate the crystallization age of the granites because they are shallowly emplaced bodies that would have cooled rapidly to ambient temperatures below 300°C. This is confirmed by U-Pb ion probe (SHRIMP-RG) dating of zircons from sample 123B64 from the
Uemliakh pluton which yielded a weighted mean $^{235}$U/$^{207}$Pb age of 121.9±2.5 Ma based on 12 zircon grains excluding 4 grains that had 154 to 135 Ma ages, probably the result of older inherited components.

We collected biotite from the last occurrence of this mineral away from the Tarbagganakh pluton (sample 99JT38 located 2.25 km west of the margin of the granite). The $^{40}$Ar/$^{39}$Ar plateau age of this sample was statistical identical to that of biotite from the granite itself. This confirms field observations that suggested that intrusion of the granite took place while ductile deformation and fabric development was occurring within the metasedimentary rocks (Fig. 13).

In summary, our $^{40}$Ar/$^{39}$Ar work in the rocks of the Allakh Yun’ and Sette Daban zones of the South Verkhoyansk demonstrate that there was a close link between intrusion of the granitic plutons of the Allakh Yun’ belt, and low-grade metamorphism and ductile deformation of the Paleozoic rocks of the Verkhoyansk continental margin. Contrary to previously reported geochronological data (Nenashev and Zaitsev, 1980) which assigned 140-143 Ma ages to the plutons on the basis of Rb-Sr data, this igneous and metamorphic event took place mostly during Hauterivian-Barremian time.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lat.</th>
<th>Lon.</th>
<th>Unit</th>
<th>Lithology</th>
<th>Setting</th>
<th>Mineral</th>
<th>Total Fusion Age (Ma)</th>
<th>$^{40}$Ar/$^{36}$Ar Plateau (Ma)</th>
<th>Steps Used</th>
<th>%$^{39}$Ar Used</th>
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</thead>
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<tr>
<td>123B62</td>
<td>138.2727</td>
<td>60.6667</td>
<td>Uemliakh</td>
<td>Granodiorite</td>
<td>Allakh Yun’</td>
<td>Biotite</td>
<td>119.4 ± 0.5</td>
<td>282 ± 37</td>
<td>120.8 ± 0.8</td>
<td>3 to 11/12</td>
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<tr>
<td>99JT22</td>
<td>138.2978</td>
<td>61.113</td>
<td>Tarbagganakh</td>
<td>Granodiorite</td>
<td>Allakh Yun’</td>
<td>Biotite</td>
<td>119.42 ± 0.5</td>
<td>254 ± 22</td>
<td>119.8 ± 0.5</td>
<td>3 to 10/11</td>
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<tr>
<td>99JT38</td>
<td>138.243</td>
<td>61.1109</td>
<td>Verkhoyansk Seq.</td>
<td>Quartzite</td>
<td>Allakh Yun’</td>
<td>Biotite</td>
<td>118.24 ± 0.5</td>
<td>147 ± 52</td>
<td>119.4 ± 0.5</td>
<td>3 to 6/7</td>
</tr>
<tr>
<td>99JT52</td>
<td>137.452</td>
<td>60.3864</td>
<td>Labystakh Fm.</td>
<td>Calc Phyllite</td>
<td>Allakh Yun’</td>
<td>Musc.</td>
<td>128.5 ± 0.4</td>
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<td>128.1 ± 0.3</td>
<td>4 to 10/13</td>
</tr>
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<td>99JT65</td>
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<td>60.1311</td>
<td>Labystakh Fm.</td>
<td>Calc Phyllite</td>
<td>Allakh Yun’</td>
<td>Musc.</td>
<td>135.8 ± 2.6</td>
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<td>151 ± 0.7</td>
<td>4 to 7/7</td>
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<tr>
<td>A-1780</td>
<td>129.2222</td>
<td>60.1351</td>
<td>Khoboityuoy</td>
<td>Granodiorite</td>
<td>West Verkh</td>
<td>Biotite</td>
<td>91.2 ± 1.2</td>
<td>322 ± 18</td>
<td>92.9 ± 0.8</td>
<td>4/8/10</td>
</tr>
</tbody>
</table>

Table 1. Summary Table for $^{40}$Ar/$^{39}$Ar Data from the Verkhoyansk

Figure 13. Small dike of granite near the margin of the Tarbagannakh pluton stretched along the foliation in the low-grade phyllites of the Carboniferous Verkhoyansk sequence. This structure is evidence that granite emplacement (at ~122 Ma) was syn- to late tectonic with respect to development of the metamorphic fabric.
(~128 to 120 Ma). Regional low-grade metamorphism in the Allakh Yun’ and Sette Daban zones of the Verkhoyansk resulted from maximum tectonic burial and peak deformation in the core of the orogen. The granitic plutons of the South Verkhoyansk were previously interpreted as collisional granites (Parfenov, 1991), however more recent geochemical data indicates that they are actually subduction-related. They probably resulted from the establishment of a new west-dipping subduction zone after accretion of the Okhotsk terrane to continental margin choked the Uda-Murgal subduction system that was active during Jurassic and earliest Cretaceous time.

Apatite Fission Track Data

We collected a 31 samples for apatite fission track determinations from the southern transect (see Fig 5 for locations). After some difficulties delays we obtained permission from the Russian authorities to ship these rocks to the USA for analysis. Our sampling strategy was to collect 5-10 kg samples of the coarsest grain sandstones found on the hanging wall and footwall of all the major thrust sheets in order to bracket any thrust-related unroofing. We also collected a set of six samples along an elevation profile from 630 to 2122 m elevation on the flank of the Tarbagannakh granite massif. After carrying out the mineral separations for apatite we found that the clean Riphean sandstones and quartzites yielded very few to no apatite grains. The fine grained Carboniferous meta-greywackies had fair apatite yield. The coarse Jurassic arkoses had unpredictable apatite content ranging from no apatite to abundant grains. The samples from the Tarbagannakh granite had excellent yield. Only seven of the viable samples have been counted at this time. Table 2 shows a summary of the sample data, and pooled fission-track age for each sample. The full data is shown in

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lon</th>
<th>Lat</th>
<th>Unit</th>
<th>Stratigraphic Age</th>
<th>Lithology</th>
<th>Setting</th>
<th>No</th>
<th>Dosimeter</th>
<th>Age</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>99JT-1</td>
<td>135.7290</td>
<td>60.6722</td>
<td>Kyllakh Fm. E. Jurassic Arkose</td>
<td>Foreland</td>
<td>13</td>
<td>1137</td>
<td>1316</td>
<td>1279500</td>
<td>3832</td>
<td>209.85</td>
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<tr>
<td>99JT-23</td>
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<td>61.1065</td>
<td>Tarbagannakh pluton, L. Cretaceous Granodiorite</td>
<td>Allakh-Yun'</td>
<td>17</td>
<td>1713</td>
<td>4830</td>
<td>1332500</td>
<td>3832</td>
<td>90.55</td>
</tr>
<tr>
<td>99JT-46a</td>
<td>137.5900</td>
<td>60.9136</td>
<td>Khamamut Fm. Mississipian Conglomerate</td>
<td>Sette-Daban</td>
<td>6</td>
<td>74</td>
<td>428</td>
<td>1353700</td>
<td>3832</td>
<td>45.00</td>
</tr>
<tr>
<td>99JT-66</td>
<td>137.1950</td>
<td>60.1264</td>
<td>Kandik Formation L. Riphean Orthoquartzite</td>
<td>4th thrust</td>
<td>1</td>
<td>333</td>
<td>1188</td>
<td>1449100</td>
<td>3832</td>
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<tr>
<td>99JT-71b</td>
<td>136.9070</td>
<td>60.1917</td>
<td>Kandik Fm. Riphean Grey quartzite</td>
<td>3rd thrust</td>
<td>7</td>
<td>50</td>
<td>183</td>
<td>1470300</td>
<td>3832</td>
<td>77.05</td>
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<tr>
<td>99JT-80</td>
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<td>60.3169</td>
<td>Kyllakh Fm. Jurassic Arkose</td>
<td>2nd thrust</td>
<td>20</td>
<td>813</td>
<td>2084</td>
<td>1491500</td>
<td>3832</td>
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</tr>
<tr>
<td>99JT-84</td>
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<td>60.4847</td>
<td>Kandik Formation U. Riphean Quartzite</td>
<td>1st thrust</td>
<td>20</td>
<td>492</td>
<td>1464</td>
<td>1304000</td>
<td>3901</td>
<td>84.01</td>
</tr>
</tbody>
</table>

NoXls: Number of crystals counted
Ns: Number of spontaneous tracks counted
Ni: Number of induced tracks counted
RhoD: Induced track density in external detector
ND: Number of tracks counted in determing ND
Age: Pooled Fission track age
Error: 1 sigma error
Zeta: 385.9

Table 2, Summary Table for Apatite Fission Track Data from South Verkhoyansk

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Appendix 3. The samples analyzed thus far are distributed across the entire transect giving a preliminary view of the exhumation history of the South Verkhoyansk. However some of the data points are of questionable quality and a final interpretation will require additional data. We will forward an update to this report once the data analyses have been completed.

The results of apatite fission track analyses are described below in order from the hinterland towards the foreland. Sample 99JT-23 collected from the Tarbagganakh pluton of granodioritic composition at 2122 m of elevation located within the Allakh-Yun structural domain. The sample yielded abundant apatite and the resulting age data is very reliable from the statistical point of view. The sample age was 90.6±2.9 Ma (Turonian), and as can be seen in the radial age plot (Fig. 15), there is a well-defined cluster of single-grain ages all within ±2σ of the pooled age. This suggests that the apatite is compositionally homogeneous and all the grains have a common closure temperature. The intrusive age of this supracrustal granite is approximated by its biotite 40Ar/39Ar age of 120±1 Ma, therefore the apatite fission track age must reflect exhumation of the granite long after its magmatic cooling had taken place. The track length histogram for this sample (Fig. 15) is very well constrained (n=150) with a symmetrical shape and moderately long mean track length of 13.3±0.1 μm with a standard deviation of 1.57 μm. The slight track reduction observed suggests moderately rapid cooling though the apatite partial annealing zone (~60-110°C) at a time slightly older than the sample AFTA age of 90.6 ±2.9 Ma. This probably signals thrust-driven uplift of the Allakh-Yun’ domain in the early Late Cretaceous.

Sample 99JT-46a was collected from Mississippian conglomerate of the Khamamut Formation of the Sette Daban structural domain. Unfortunately this sample yielded little apatite, only six grains could be counted yielding a pooled age of 45.0±5.7 Ma. The single grain ages are considerably scattered and have large errors (Figure 14), therefore the pooled age must interpreted with caution. Nevertheless it is important to note that this fission track age hints at an Early Tertiary denudation event within the Sette Daban. The most likely cause for such an event is deformation associated with left-lateral strike-slip motion on the Burkhala fault which has a prominent geomorphic expression. Analyses of other samples from the Sette Daban are required to test this hypothesis.

Sample 99JT-66, collected from quartzite of the Late Proterozoic (Riphean) Kandik Formation of the Fourth thrust sheet, yielded a single apatite grain. This grain had abundant tracks allowing a relatively precise age determination of 78±5 Ma. This sample indicates late Cretaceous (Campanian) denudation and may indicate the forward propagation of the thrust belt towards the foreland. Again given the paucity of apatite in this sample more analyses from this area are need before proposing a solid interpretation.
Figure 14. Radial plots of apatite fission track samples from the South Verkhoyansk. The vertical axis is uncertainty in sigma units, the horizontal axis is age/error. Grains with large errors plot near the origin. Isochrons fan radially from the origin. Points of a single grain population should fall within a swath of +/- 2 sigma of the sample age. This plot helps discriminate populations of grains with different closure temperatures that may be affecting the total age of the sample.
Sample 99JT-71b was also collected from the Kandik Formation, but in the Third thrust sheet. The

![Fission track length histograms for samples from the South Verkhoyansk.](image)

Figure 15. Fission track length histograms for samples from the South Verkhoyansk. Mean, refers to the mean track length represented by a dashed line on each plot. n, is the number of tracks measured.
few apatite grains in this sample had low U content and few tracks. For this reason, the single-grain ages have very large errors and are widely scattered. The pooled age of 77 ± 12 Ma must be interpreted with caution, although at least it is consistent with the age derived from the sample from the Fourth thrust.

Sample 99JT-80 was collected from arkoses of the Early Jurassic Kyllakh Formation in the footwall of the Second thrust. The pooled age of this sample is 111.4 ± 4.9 Ma. As can be seen in the radial plot (Fig. 14) there are three population of single-grain ages. Although most of the grains (13/20) yield mid-Cretaceous ages, a few grains are Tertiary (3/20), and a few are Jurassic (4/20). The vitrinite reflectance value from coal in the Kyllakh Fm. of the First thrust sheet is 0.8, indicating a maximum paleotemperature of about 120°C using the vitrinite maturation model of Sweeney and Burham (1990). Therefore sample 99JT-80 would be at the upper boundary of the partial annealing zone for apatite. As is common for detrital samples, it is likely that this rock contained a mixture of apatites of varying composition. The most retentive grains were probably not completely annealed prior to the onset of thrusting in the Verkhoyansk. The Tertiary grains would be the least retentive and may record a younger event. The track length distribution of this sample is broad (std. dev. = 1.99μm), negatively skewed, and with a mean track length of only 12.9 ± 0.33μm. This is evidence for long residence within the partial annealing zone, therefore the sample age can not be interpreted directly as dating a rapid cooling event.

Sample 99JT-84 was collected from quartzite of the Late Proterozoic Kandik Formation in the frontal part of the first thrust sheet. The pooled age for this sample is 84.0 ± 4.6 Ma, and the quality of the data is fairly reliable. However, as can be seen in the radial plot (Fig. 14), the single grain ages are not homogeneous. One Jurassic and one Early Tertiary single grains ages fall outside of the 2σ swath. Excluding these two data points from the calculation yields a corrected pooled age of 80.8 ± 4.6 Ma. The track length distribution of these sample is also broad, and negatively skewed (Fig. 15). These patterns suggest long residence within the partial annealing zone and slow rates of cooling, however there are too few track measurements available in this sample to offer a more quantitative assessment.

Sample 99JT-1 collected form arkosic sandstone of the Kyllakh Formation in the foreland yielded a pooled age of 209.9 ± 9.2 Ma. Because the apatite fission-track age overlaps with the stratigraphic age of the Kyllakh Formation (Hettangian-Sinemurian), it is clear that the rocks did not undergo sufficient burial to reset the fission track system. This is consistent with the vitrinite reflectance values from coals collected nearby (Ro=0.47) which indicate a maximum paleotemperature of about 60°C. The apatite age of this sample reflects denudation prior to sedimentation of the Kyllakh during the passive margin stage of the Siberian platform.

The apatite fission track ages collected so far from the South Verkhoyansk range support the
Figure 16. Simplified geological map showing the distribution of thermal maturity data. CAI are conodont alteration indices keyed by color to the degree of alteration. RO are vitrinite reflectance samples keyed to the reflectance value, the numbers are sample numbers plotted on Table 3. See Fig. 6 for a key to the geological units.
Sample 99JT-1 collected form arkosic sandstone of the Kyllakh Formation in the foreland yielded a pooled age of 209.9±9.2 Ma. Because the apatite fission-track age overlaps with the stratigraphic age of the Kyllakh Formation (Hettangian-Sinemurian), it is clear that the rocks did not undergo sufficient burial to reset the fission track system. This is consistent with the vitrinite reflectance values from coals collected nearby (Ro=0.47) which indicate a maximum paleotemperature of about 60°C. The apatite age of this sample reflects denudation prior to sedimentation of the Kyllakh during the passive margin stage of the Siberian platform.

The apatite fission track ages collected so far from the South Verkhoyansk range support the conclusions listed below. Rocks in the hinterland of the orogen (Allakh Yun’ domain) had been exhumed to within a few kilometers of the surface by about 90 Ma. Given the regional low-greenschist metamorphic grade of the area, this required the erosional removal of about 10 km of structural section. The shortened mean track length of the sample from the Tarbagganakh granite suggests that cooling rate was moderate, therefore the onset uplift, and presumably thrusting, may have predated 90 Ma by a few million years. We will be able to quantify the cooling rates through modeling of the track length distributions once mere data is collected. Three samples form the frontal thrust sheets have fission-track ages of about 80±5Ma. Younging of the fission track ages towards the foreland probably reflects the west-ward propagation of the thrust front through the Late Cretaceous (Fig. 16). Thus, even though the $^{40}\text{Ar}/^{39}\text{Ar}$ ages of metamorphic rocks of the Allakh-Yun’ domain indicate that ductile strain and metamorphism was taking place during Early Cretaceous time supracrustal deformation in the thrust belt was younger. One fission-track age from the Sette-Daban domain hints that an Early Tertiary denudation event affected that portion of the Verkhoyansk. The most likely cause of uplift during that period is transpressional deformation associated with movement of the Burkhala strike-slip fault.

Conodont Alteration Indices

During our field work in the South Verkhoyansk, V. Tarabukin, a conodont specialist from the Diamond and Precious Metal Geology Institute, collected samples from the Ordovician through Devonian carbonates of the Sette Daban zone (see Fig. 16 for sample locations). He later separated conodonts from these rocks and established the degree of thermal maturity by determining the conodont alteration indices (CAI). In the Sette Daban, all rocks have variously developed metamorphic cleavages, and fine grained units usually display penetrative phyllitic or slaty cleavage. Fine metamorphic chlorite and sericite are common. These observa-
tions are borne out by the degree of thermal maturity of the rocks. CAIs range from 5.0 to 6.0, which translate to maximum paleotemperatures of 300 to 360°C assuming protracted heating, according to the calibration of Rejebian and others (1987). Although the thermal maturity data is not evenly distributed through the map area, there appears to be a high concentration of high CAIs in the headwaters of the Sahara River, at about 61°N. Since there are no plutonic rocks in the Sette Daban zone, we conclude that high paleotemperatures were caused by tectonic burial during the development of the thrust-belt. Assuming a paleogeothermal gradient of 30°C/km this would imply that 10 to 12 km of structural section might have been stripped by erosion from the top of the Sette Daban structural fan (see Fig. 17).

Vitrinite Reflectance

The Early Jurassic sandstones of the Kyllakh and Krasnoaldan Formations have abundant coaley plant remnants. We sampled these units along the Allakh Yun’ River both in the hanging wall of the frontal thrust and in the undeformed foreland and along the bluffs of the Aldan River south between Eldikan and the mouth of the Allakh-Yun’ (see Fig. 16 for locations and Table 3 for summary of results). The vitrinite reflectance of these samples was determined at the Core Laboratories at Carrollton, TX.

As might be expected the highest Ro value corresponds to the most internal sample (99JT82) collected from the frontal thrust sheet. This sample had Ro of 0.8 which is within the oil window. The rest of the samples are all immature with Ro values ranging between 0.47 and 0.57. Using the vitrinite maturation model of Sweeney and Burham (1990) the maximum paleotemperatures attained by the foreland samples were about 80°C and by sample 99JT82 about 120°C. Assuming a geothermal gradient of 25°C/km and 0°C average surface temperature, maximum burial ranged from 3.2 km in the foreland to 4.8 km in the frontal thrust sheet (see Fig. 17).

As discussed above, the one apatite fission track sample from the foreland yielded a Jurassic age, confirming that the rocks were never deeply buried. The maximum stratigraphic thickness of Middle Jurassic units reported in this part of the foreland is 3 km, therefore it can account for most of the paleoburial. This confirms that no foreland basin existed in front of the South Verkhoyansk and that the lack of such a basin today is not related to lack of preservation and post-tectonic uplift.
Figure 17. Structural cross section using the paleotemperature data to control maximum burial. Burial was calculated assuming a geothermal gradient of 25 deg./km in the foreland and 30 deg./km in the hinterland. See Fig. 3 and 6 for location.
Table 3. Vitrinite Reflectance Data
Verkhoyanks fold belt, Yakutia

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Lon</th>
<th>Lat</th>
<th>Sample Type</th>
<th>Mean Reflectance</th>
<th>Number of Readings</th>
<th>Standard Deviation</th>
<th>Remarks</th>
</tr>
</thead>
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