SEISMICITY OF THE AMERASIAN ARCTIC SHELF AND ITS RELATIONSHIP TO TECTONIC FEATURES

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ABSTRACT

The Arctic Ocean margins of Chukotka and Alaska appear to be dominated by extensional stresses. The focal mechanism of the Barter Island earthquake, northeast Alaska, indicates north-south tension and listric normal faulting. Off Chukotka, the extension axis strikes northwest and is a continuation of the extensional stress field of western Alaska. The New Siberian Islands region, in contrast, shows transpressional faulting as a result of spreading-related compression acting on potential late Mesozoic zones of weakness.

INTRODUCTION

The general seismicity of the Arctic has recently been summarized by Wetmiller (1978) and Fujita et al. (1990a) and shows that the seismicity along the Arctic Mid-Ocean Ridge is well defined and similar to that of other mid-oceanic ridges, although with a smaller number of transform earthquakes (Fig.1). The seismicity of the Arctic continental margins and shelves, however, is less well known. Best known is the Canadian Arctic margin, where magnitude 7.3 earthquakes have been reported. However, most of the seismicity is very weak (about magnitude 2-4), and is concentrated in clusters just off the continental slope (Basham et al., 1977). Many earthquakes along the slope off the Queen Elizabeth Islands are associated with positive free-air gravity anomalies and have been explained as a result of sediment loading (Basham et al., 1977) or glacial rebound (Wetmiller and Forsyth, 1982; Stein et al., 1979). Less studied is the seismicity along the Alaskan continental margin and in the East Siberian and Chukchi seas. This paper summarizes the seismicity of the latter regions and presents focal mechanisms for the largest events based on combined Russian and worldwide data.

BARTER ISLAND, ALASKA

The largest cluster of offshore seismicity along the Alaskan continental margin occurs off Barter Island, Alaska, where a sequence of moderate earthquakes occurred about 25 km offshore in 1968 (Fig.2). The cluster is located on the southern edge of a 90 mGal (Rupple and McHendrie, 1976) free-air gravity anomaly and along the offshore extension of the Canning Displacement Zone (Grantz and May, 1982; Grantz et al., 1983), a possible tectonic boundary separating the tectonically active northeastern portion of Alaska (Biswas et al., 1977) from the passive north slope of Alaska. The epicentral region is microseismically active and is where the Pacific deformation front penetrates to the northern edge of Alaska (Grantz et al., 1983).

The m_b 4.4 mainshock of the Barter Island sequence occurred on January 22, 1968. Despite the low body-wave magnitude, this event shows significant surface wave at teleseismic stations. This suggests that the event is shallow (< 5 km) and, based on a noisy surface wave amplitude radiation pattern, Cook (1988) suggested that one of the nodal planes is oriented at approximately 100° azimuth. Using P-wave first motions at Canadian and Worldwide Standardized Seismograph Network (WWSSN) stations, Cook (1988) and Biswas et al. (1986a) suggest strike-slip solutions for this event, although the strikes of the nodal planes differ. The Biswas et al. (1986a) solution has a north-south striking

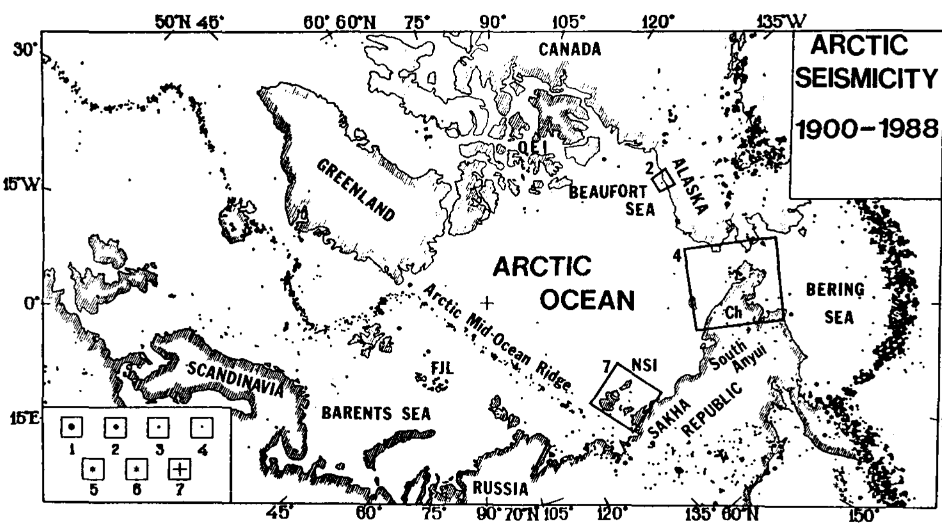

Fig.1. Arctic seismicity (1900-1988). Dots show epicenters of shallow focus (0 - 60 km) earthquakes (symbols indexed in lower left corner are by magnitude, M, 1 - M ≥ 7.0; 2 - 6.0 ≤ M ≤ 6.9; 3 - 5.0 ≤ M ≤ 5.9; and 4 - 4.0 ≤ M ≤ 4.9); stars represent intermediate (5 - 60 < h ≤ 300 km) and deep (6 - h > 300 km) events. The cross (7) denotes the north pole Boxes show areas of Figs.2, 4, and 7. QEI denotes Queen Elizabeth Islands, Ch - Chukotka, NSI - New Siberian Islands, and FJL - Franz Joseph Land (after Imaev et al., 1990).

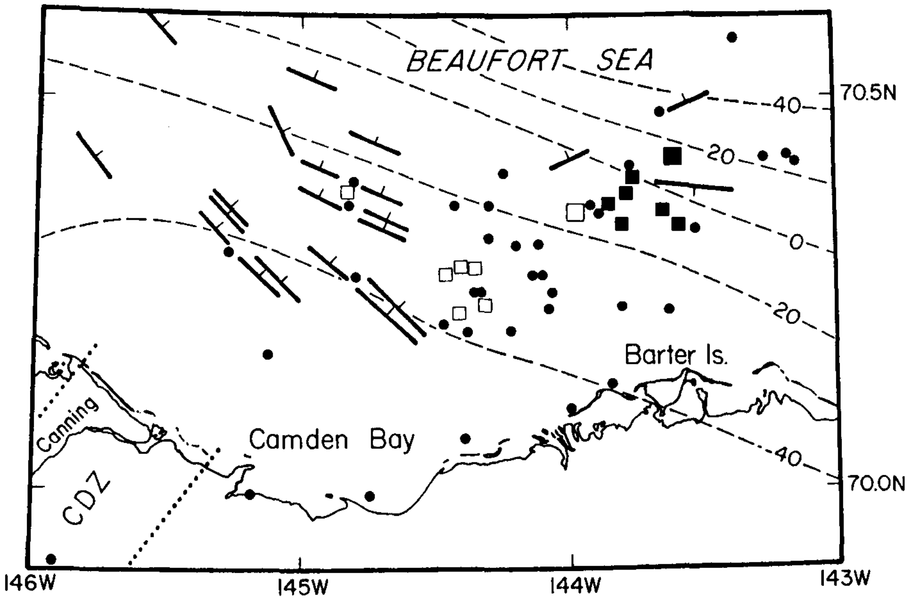

Fig.2. Seismicity and structures of the Barter Island region. Epicenters of earthquakes (solid circles) not in the 1968 Barter Island sequence shown by solid dots (from Grantz et al., 1983). Epicenters of the 1968 sequence relocated using the mainshock located with all data listed in the ISC Bulletin as a master event shown by open squares (mainshock denoted by larger square). Epicenters of the 1968 sequence relocated using the mainshock located with only regional stations (Δ < 23.6°) as a master event shown by solid squares (mainshock denoted by larger square). Thick solid lines denote normal faults, bar on downthrown side (from Grantz et al., 1983). Dotted lines denote boundaries of the Canning Displacement Zone (CDZ) of Grantz and May (1982). Dashed lines show the Free Air Gravity anomaly in mGal from Rupple and McHendrie (1976).

compressional axis, while the Cook (1988) solution has one striking northwest. Both of these mechanisms are constrained by the compressional first motions reported in the International Seismological Center (ISC) Bulletin at Yakutsk, Bodaibo, and Semipalatinsk, Russia, and Quetta, Pakistan. As a result of these compressions, the dilatations reported from Tiksi, Russia, and Barrow, Alaska, were ignored.

Examination of seismograms recorded by the Yakut Regional Network in northeastern Russia, however, calls this interpretation into question. Four stations were operative in Yakutia (now the Sakha Republic) in 1968: Yakutsk, Ust' Nera, Chul'man, and Ust' Nyukzha. The event was not clearly recorded at either Ust' Nyukzha or Yakutsk; the former is very noisy and the latter has a weak emergent phase. However, Ust' Nera shows an emergent dilatation while the Chul'man record is a very clear dilatation. The polarity for Ust' Nera was verified against teleseisms and for Chul'man using both teleseisms and a local explosion. The WWSSN record at Quetta is noisy, and any first motion pick is uncertain. Thus, the only reliable first motions in the 280-300° azimuth range are dilatational.

We also examined records from the Alaska Network (AKNet). They show a mixed set of arrivals; many could be described as nodal with a very weak first pulse. Two stations, the WWSSN station at College and the AKNet station at Sheep Creek Mountain, show dilatations, while Pedro Dome shows a compression. Compressions also are possible, although less certain, at Black Rapids and Tanana. Seismograph polarities were verified against Nevada Test Site nuclear detonations. These data, combined with first motions examined from Canadian stations by Cook (1988), indicate that the Barter Island mainshock was a normal faulting event (Fig.3) and had a tension axis striking about 355°.

All of the teleseismic Barter Island events are poorly recorded and appear to have a precursory phase recorded only at regional stations. Because of this phase, the absolute location of the 1968 mainshock is poorly determined. Two sets of relocations were calculated for the teleseismic aftershocks of the 1968 event using the master event technique. The first used all reported data to locate the mainshock and used the residuals from that solution as path corrections for the aftershocks (open squares in Fig.2). In the second set, only regional stations (Δ < 23.6°) were used to locate the mainshock, as these stations were more likely to record the precursory phase. The aftershocks were relocated relative to this second solution (solid squares). Based on the second relocation, the aftershocks appear to align along a trend of about 290°, although the mainshock lies off this trend and there is considerable scatter. Alternatively, four of the six aftershocks and the mainshock could be interpreted as lying on a strike of 60°. We favor the northerly dipping plane striking 290° to be the fault plane because it is consistent with seismic-reflection profiles that show seaward-dipping listric normal faults in the epicentral area (Fig.2, Grantz and May, 1982) and the shallow depth of the event.

Estabrook (1985) determined a focal mechanism for an event (December 12, 1978) about 100 km to the south for which one possible solution has nearly the same T-axis azimuth and for another event (March 31, 1975), very close to Barter Island, that also is a normal fault, although the T-axis trends to the north-northeast. Thus, while most geologic structures in northern Alaska appear to be compressional, the present-day stress regime on the Beaufort shelf off Barter Island appears to be extensional.

CHUKCHI SEA

An enigmatic cluster of earthquakes occurs off of Kolyuchin Gulf, eastern Chukotka (Fig.4). This region is very active seismically, with four events of magnitude 5.5-7 in 1928, magnitude 5.5 events in 1962 and 1971, and several smaller events of magnitude less than 5. In addition, a number of very small (m_b < 2) events have been reported from this area by the Iul'tin (ILT) seismic station. The microseisms probably were located using P-wave polarization angles observed at the three-component station ILT and the locations of these events may be poor. Much of the microseismicity in the area northwest of Iul'tin reflects mining activities (V. A. Bobrobnikov, pers. commun., 1991).

The October 5, 1971, event (m_b 5.2, M_s 5.0) is the only one for which a significant body of data is available. Three different focal mechanisms have been proposed for this event. Coley (1983) proposed a strike-slip solution, with one plane oriented about 300°. Fujita et al. (1983) used the same data to suggest a normal faulting mechanism, also with one plane oriented about 300°. Biswas et al. (1986a) suggested a normal faulting mechanism with both nodal planes striking 63°. Surface wave analysis failed because the Rayleigh waves from this event are superimposed on those from an event in the Aleutian Islands and could not be separated.

Examination of Yakut and Alaskan first motions clearly eliminates the strike-slip solution of Coley (1983) because most of the Alaskan stations and all of the Yakut first motions are dilatational. The resulting first motions (Fig.5) strongly support the Biswas et al. (1986a) mechanism with only minor deviations. Although there is some play in the orientation of the nodal planes, a strike of 232° and dip of 35° NW. with a rake of 270° fits the data very well.

This solution, however, has nodal planes oriented perpendicular to the strike of the most prominent structural feature in the area, the subsurface Kotzebue arch (Eittreim et al., 1979) and to most major faults in Chukotka (Kosygin et al., 1977). In addition, while the orientation of the T-axis (strike 322°) is consistent with the maximum horizontal stress orientations observed in northwestern Alaska and Seward Peninsula (Nakamura et al., 1980; Zoback, 1992), it is the compressional or intermediate stress that elsewhere has a west to northwest strike. Focal mechanisms of earthquakes occurring in Seward Peninsula have a wide variation of T-axis orientations (Biswas et al., 1986a,b). However, the mechanism of the largest earthquake studied in northwest Alaska, the magnitude 7.3 Huslia earthquake of 1958 (66° N., 157° W.) determined using P-wave first motions, indicates a T-axis orientation of about 333° (Wickens and Hodgson, 1967). In addition, one possible mechanism for a cluster of earthquakes that occurred in western Seward Peninsula has a T-axis orientation of about 300°, although it is very poorly constrained (Biswas et al., 1986b). Thus, the principal stress field in the region could be northwest-striking tension.

We also reexamined records for the magnitude 5.5 event of March 4, 1962. Of the stations we have been able to reread, two western U.S. stations and Yakutsk are dilatational. The bulletin of the Tiksi seismic station also reports a dilatation, and the record at Ammonal'naya (Ust' Nera) is ambiguous, although it appears compressional. Disregarding the last station, the first motions confirmed and reported in the International Seismological Summary indicate that a focal mechanism nearly identical to that of the 1971 event is possible (Fig.6).

Records for the 1928 events are very scarce, and most stations were too far away to record the first motion well. No first motions were visible on the records for Pasadena, Riverside, and Santa Barbara, California, and Tokyo, Japan, for any of the events. However, based on horizontal components, the first motion at Tucson, Arizona, is apparently compressional for the February 21, 1928, magnitude 6.9 event. If this first motion is reliable, and the event had a mechanism similar to those in 1962 and 1971, the southeast-dipping plane requires a steeper dip. It is more likely that as a result of the low amplitudes, the first motion was not observed. On the Albuquerque record for the 1962 event, the first down-swing is about one-fifth the amplitude of the following up-swing and the Tucson record for the 1962 event also appears compressional.

While the 1982 events were too small to determine a focal mechanism, AKNet data and bulletin-reported data from Russia are not inconsistent with a normal faulting mechanism.

Seismic-reflection work in the Chukchi Sea indicates faults that cut into some Quaternary sediments (Eittreim et al., 1979; Shipilov, 1990), and some northeast-trending faults are mapped on land in Chukotka. An extensional regime in western Alaska appears to have developed in the late Cenozoic (Nakamura et al., 1980). It is likely that these events represent the superposition of a new stress regime off Chukotka as well. The exact stress-generating mechanism for this event is not known, but Andreev et al. (1980) note that these events occur in a region where there are gravitational anomalies and a gradient in the uplift rates.

NEW SIBERIAN ISLANDS REGION

Most of the seismicity of the New Siberian Islands region is concentrated west of Kotel'nyi and Stolbovoi Islands and is associated with the formation of deep grabens at the eastern edge of the Laptev Sea rift system (Fujita et al., 1990b). The Yakut Local Network has recorded a low level of seismic activity around the

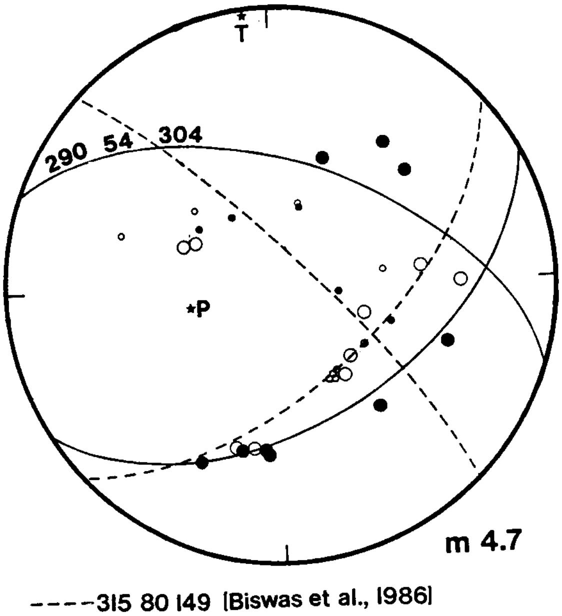

Fig.3. Focal mechanism of the Barter Island main-shock of January 22, 1968. Lower hemisphere projection. Large dots are first motions reread from seismograms, small dots are bulletin-reported first motions. Solid dots show compressions, open circles show dilatations. Stars denote P and T axis locations. Solid lines show best fit nodal planes; dashed lines show nodal planes from solution of Biswas et al., 1986. Focal mechanism parameters given as strike, dip, rake.

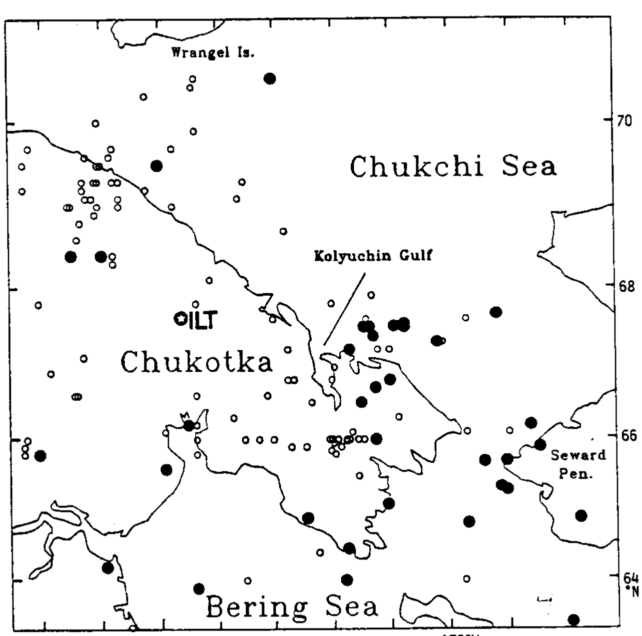

Fig.4. Seismicity of the Chukchi Sea from the ISC catalog (solid circles) and Zemletryaseniya v SSSR, 1964-1987 (open circles).

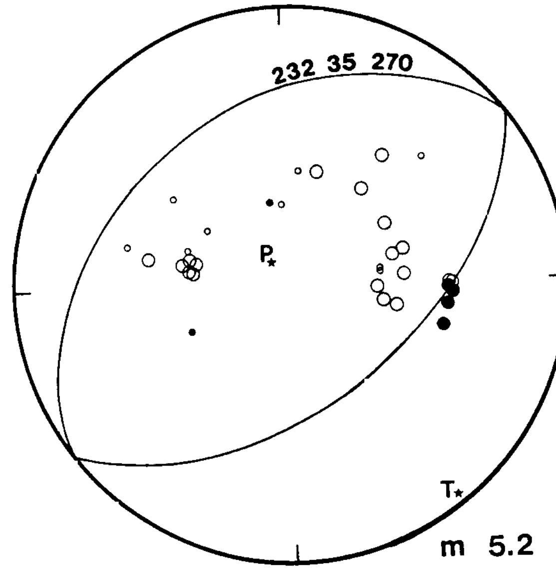

Fig.5. Focal mechanism of the Chukchi Sea event of October 5, 1971. Symbols and conventions as in Fig.3.

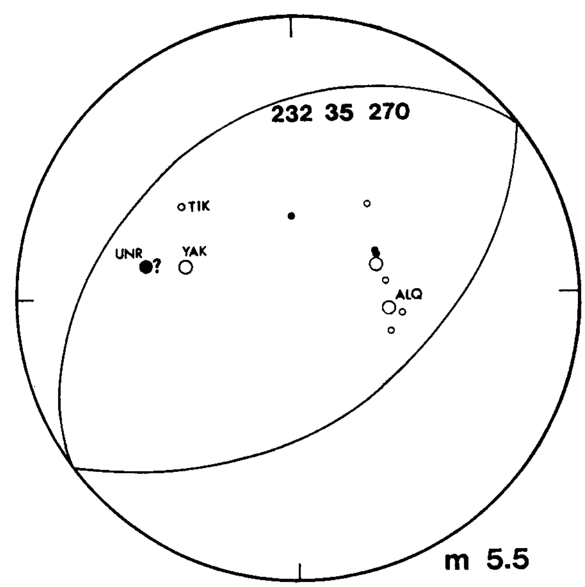

Fig.6. Focal mechanism of the 1962 Chukchi Sea event. Symbols and conventions as in Fig.3.

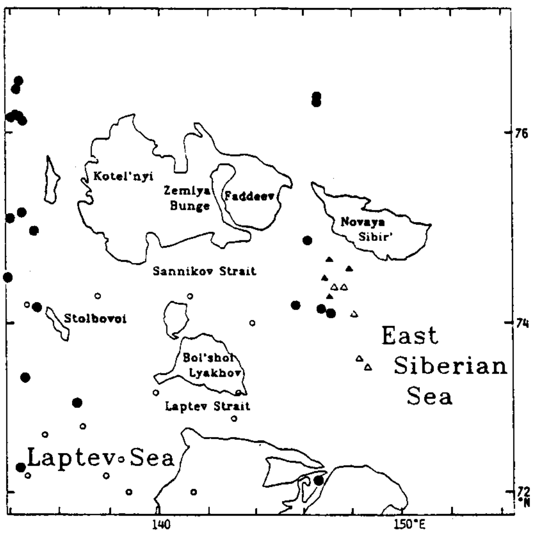

Fig.7. New Siberian Islands Seismicity from teleseismic (ISC, USGS; solid circles), regional network (Zemletryaseniya v SSSR, 1964-1987; open circles), and temporary deployment (solid triangles - epicenter given by Avetisov, 1975; open triangles - epicenters calculated from data in Avetisov, 1975).

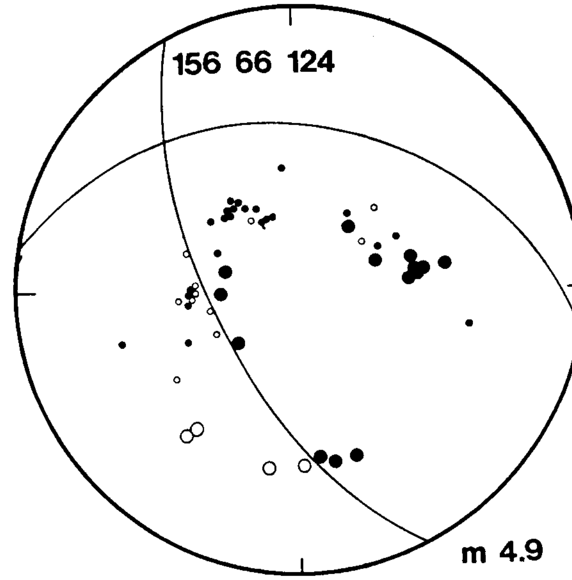

Fig.8. P-wave focal mechanism of the New Siberian Islands event of December 15, 1973. Conventions and symbols as in Fig.3.

Lyakhov Islands; however, a series of small teleseisms define an apparent north-south trend between Novaya Sibir' and Faddeev Islands (Fig.7).

The largest earthquake in the East Siberian Sea occurred on December 15, 1973 (m_b 4.9). Based on bulletin-reported first motions, Avetisov (1978) proposed a left-lateral strike-slip mechanism with motion parallel to the strike of Sannikov Strait. Using WWSSN, Yakut network, and bulletin-reported first motions, Koz'min (1984) and Cook (1988) determined nearly identical mechanisms for this event: a thrust with some strike-slip component. Combining the teleseismic results of Cook (1988) and the regional data of Koz'min (1984) allows some refinement of the mechanism (Fig.8). The P-wave mechanism is supported by the Rayleigh wave radiation pattern (Cook, 1988), although the station distribution is poor. The inferred fault plane of this solution (156/66/124) is constrained by first motions from the Yakut network, which plot as crustal refractions. The auxiliary plane is unconstrained, other than by apparent dominance of compressions in the center of the focal sphere.

To better constrain this mechanism, short-period synthetic seismograms were computed for Shiraz, Iran (SHI), and Golden, Colorado (GOL); only these two stations recorded waveforms that could be modeled, and even these were marginal. Both records appear to show moderately sharp upward first motions, but an attempt to model them using the thrust mechanism discussed above was unsatisfactory. Examination of the records indicates that SHI has a very weak initial downward motion prior to the compression. A similar interpretation is possible at GOL, although the background noise at this station is higher. These observations can be modelled by placing both stations near a nodal plane and interpreting the compression as a depth phase. Fair to good fits to the observed waveforms (Fig.9) are then obtained with a strike-slip mechanism (271/77/30) very similar to that of Avetisov (1978). Many of the stations reporting compressions in the ISC Bulletin lie along the nodal planes of this mechanism, and may be the result of identifying a depth phase as the first arrival. Although the small size of this event makes it difficult to resolve a definitive solution,

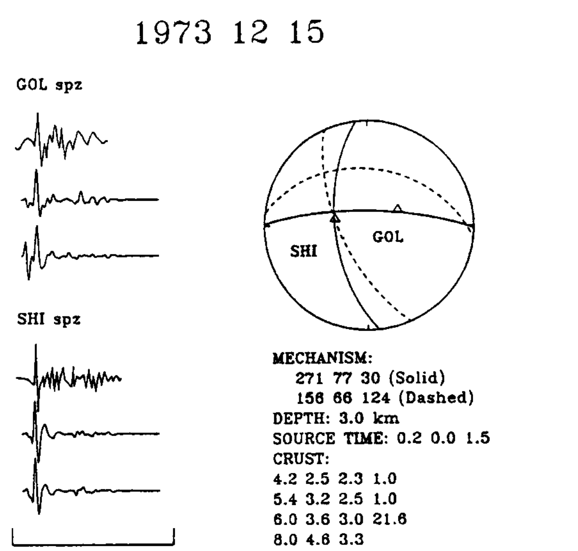

Fig.9. Short-period synthetic seismograms for the 1973 New Siberian Islands event. Observed (top trace) and synthetic traces for two mechanisms (solid line and middle trace, Avetisov, 1978; dashed line and bottom trace, Koz'min, 1984) for two stations. Crustal structure (α = P-wave velocity in km/sec, β = S-wave velocity in km/sec, ρ = density in gm/cm^3, and T = layer thickness in km), and trapezoidal source time function (rise, flat, fall in sec) given at right. Other conventions as in Fig.3.

it is most likely transpressional with significant strike-slip motion.

Avetisov (1975) operated temporary, two-station deployments on the Anjou and Lyakhov Islands in the spring of 1974 and 1975 and reported numerous aftershocks from the source region of the 1973 event. Based on data presented in Avetisov (1975), we located some of the aftershocks (Fig.7), assuming that they occurred in the region of the 1973 mainshock. They also define a nearly north-south trending lineament that aligns with the north-south striking nodal plane, although the station distribution in 1974 was such that the location uncertainties are in the north-south direction. The north-south trend is concurrent with that of the extension of the South Anyui suture zone in the East Siberian Sea proposed by Spektor et al. (1981). Thus, these earthquakes may represent reactivation along this Cretaceous zone of weakness resulting from off-ridge compressional stresses arising from rifting along the extension of the Arctic Mid-Ocean Ridge in the Laptev Sea.

CONCLUSIONS

Events along the Alaska and Chukotka margins are extensional and appear to represent a recent superposition of extensional stresses on previously compressional regimes. The Barter Island event is consistent with shallow listric normal faulting with a north-south oriented T-axis. The Chukchi Sea events all appear to be normal faults with a northwest-striking T-axis, and the New Siberian Islands events are transpressional and may represent ridge-spreading stresses released along an extension of the Cretaceous South Anyui suture zone.

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