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UNUSUAL EARTHQUAKES IN THE GULF OF ALASKA AND FRAGMENTATION OF THE PACIFIC PLATE

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Abstract. Two recent M_S 7.6 strike-slip earthquakes in the northern Gulf of Alaska ruptured a composite 250-km-long north-striking zone in the Pacific plate. These shocks are attributed to a combination of enhanced tensional stress in the Pacific plate seaward of and following the great (M_W 9.2) Alaska earthquake of 1964, and compressional stress resulting from collision of the Yakutat terrane with North America. The occurrence of these shocks reflects fragmentation of the northeast corner of the Pacific plate, possibly the initial step in establishing a new plate boundary seaward of the current boundary.

Introduction

Major ($M_S \geq 7.5$) oceanic intraplate earthquakes are rare, occur mostly beneath and just seaward of oceanic trenches in active subduction zones, and typically involve normal or thrust faulting (Chapple and Forsyth, 1979; Bergman, 1986; Christensen and Ruff, 1988; Lay *et al.*, 1988). We report here the unusual occurrence of two M_S 7.6 strike-slip earthquakes with a total seismic moment of 1.2×10^{21} N m (Table 1) near the Yakataga seismic gap.

The earthquakes occurred seaward of the complex transition between the transform and convergent plate boundaries near the eastern end of the Aleutian arc (Figure 1, Table 1). East of about longitude 140°W, the north-northwestward motion of the Pacific relative to the North American plate results in dextral slip along the Fairweather-Queen Charlotte fault system, the northern part of which ruptured in an M_S 7.9 event in 1958. West of longitude 144°W, motion is accommodated by underthrusting and subduction along the Aleutian megathrust, which last slipped in the 1964 earthquake. In the intervening region, which has been identified as a seismic gap (Tobin and Sykes, 1968; Kelleher, 1970; Sykes, 1971), the tectonics are complicated by the collision of the Yakutat terrane, which moves with nearly the Pacific plate velocity (Plafker *et al.*, 1978; Lahr and Plafker, 1980; Perez and Jacob, 1980; Bruns, 1983; Plafker, 1987). Although no great earthquake has occurred within the Yakataga seismic gap since the turn of the century (McCann *et al.*, 1980), two sequences with low-angle thrusting have occurred there since 1964: an M_S 6.8 shock in 1970 beneath the Pamplona zone (Perez and Jacob, 1980), and an M_W 7.5 shock in 1979 along the eastern margin of the gap (Lahr *et al.*, 1980).

Observations

The recent Gulf of Alaska sequence was well recorded by the southern Alaska seismograph network. Using P and S phases recorded by this network, we located epicenters for the mainshocks and their aftershocks with an assumed velocity model (7 km of 5.0 km/s, 5.5 km of 6.8 km/s, and 8.1 km/s half-space). Three of the Gulf shocks were located teleseismically and used as master events to compute local station travel-time corrections. Focal depths were fixed at 10 km. Synthetic modelling suggests that there may be as much as 10 - 20 km of relative error in latitude but typically less than 10 km in longitude. We also determined fault-plane solutions from initial P-wave polarities recorded by the network and those reported at teleseismic stations.

TABLE 1. Focal parameters of recent Gulf of Alaska earthquakes

DATE	ORIGIN TIME UTC hr:mn:sec	EPICENTER Lat,°N	Lon,°W	MAGNITUDE m_b	M_S	MOMENT* (N·m 10^{20})	FAULT LENGTH km	FAULT PLANE Strike deg	Dip deg	SLIP Rake deg
871117	08:46:50.89	58.80	143.11	6.6	6.9	0.66	40	275	83	2
871130	19:23:16.39	58.91	142.76	6.7	7.6	7.3	140	171	90	166
880306	22:35:36.38	57.23	142.78	6.8	7.6	4.9	110	175	69	-178

Epicenters computed from published PDE EDR P-phases in the distance range 30° to 100° with Herrin (1968) traveltimes and station corrections derived from a large aftershock of the 1979 St. Elias earthquake, whose location at 60.2°N, 141.3°W was well constrained by the regional network. Depths fixed at 10 km.
*HRV Centroid Moment Tensor, Best Double Couple

The sequence (Figure 2) began with an M_S 6.9

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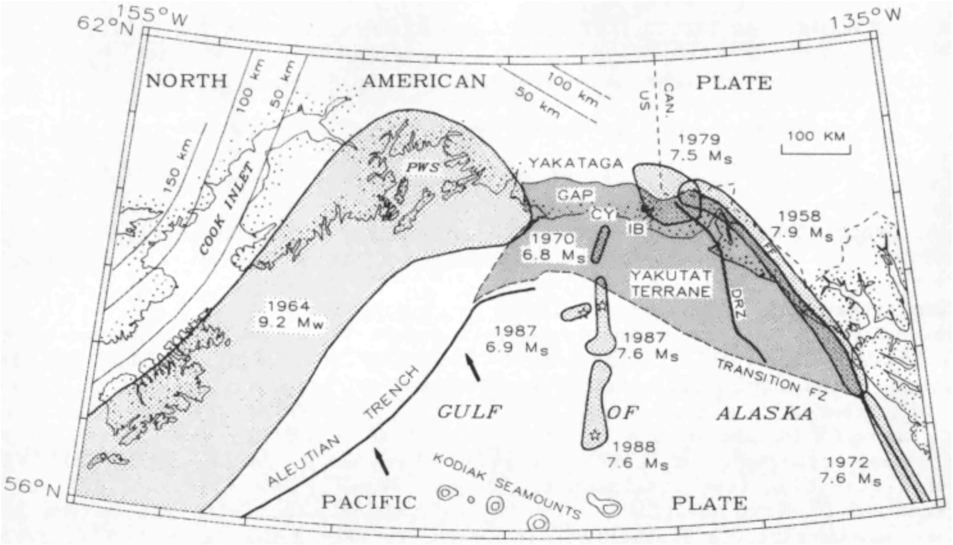

Fig. 1. Map of Gulf of Alaska region showing locations of recent shocks (epicenters shown as stars) in relation to the Pacific and North American plates, Yakutat terrane (dark shading), rupture zones of large historic earthquakes (light shading), Yakataga seismic gap, and Aleutian and Wrangell Wadati-Benioff zones (depth contours on top of zone). Heavy arrows show relative motion of Pacific plate with respect to North American plate (Minster and Jordan, 1978). PWS = Prince William Sound; DRZ = Dangerous River zone (Plafker, 1987); IB = Icy Bay; CY = Cape Yakataga; FF = Fairweather fault.

event on November 17, 1987, which involved sinistral slip on a 40-km-long, nearly east-west-trending zone. This was followed on November 30, 1987 and on March 6, 1988, by M_S 7.6 earthquakes which jointly ruptured a 250-km-long, north-striking fault zone.

The first M_S 7.6 earthquake was a complex event (USGS Preliminary Determination of Epicenters, Monthly Listing, November 1987): the epicenter of the initial energy was located 30 km ENE of the earlier M_S 6.9 event. Aftershocks from the first 6 hr extend about 40 km north and 100 km south of the initial event. The aftershock distribution and focal mechanism of the November 30 shock constrain the slip to be dextral on a nearly vertical plane.

The second M_S 7.6 event apparently involved unilateral rupture to the north along a zone parallel to, but offset about 15 km westward from, the November 30 sequence. Most of the aftershocks in the first 6 hr occurred in a diffuse group near the mainshock or in a tight cluster about 70 km to the north, near the largest aftershock (6.2 m_b) The mainshock focal mechanism and aftershock

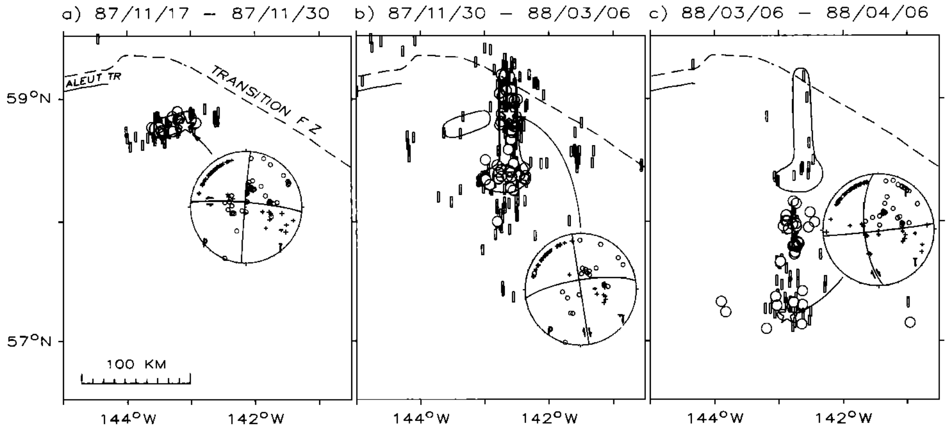

Fig. 2. Aftershock distributions and fault plane solutions for each of three mainshocks. Each frame begins at time of mainshock (star); circle = epicenter during first 6 hrs; rectangle = subsequent epicenter. Note the narrowness of the main north-south rupture zone (b and c), the existence of cross-cutting seismicity near latitude 58.3°N (b), the western offset in the principal zone of seismicity south of latitude 58.2°N (c), and the occurrence of off-fault seismicity (b and c). Fault-plane solutions are lower-hemisphere, equal-area projections of first motions from southern Alaskan and teleseismic stations (plus = compression, circle = dilatation).

distribution also indicate dextral slip on a vertical fault.

Discussion

Historical earthquakes as large as m_b 5.3 have been located in the vicinity of the recent shocks; however, the epicenters are too few and too scattered to define any seismogenic structures. Bathymetric data from the epicentral region are sparse and reveal no obvious structural features with which to associate these recent earthquakes. Linear magnetic anomalies in the epicentral region (Schwab *et al.*, 1980) parallel the north-south ruptures, suggesting that this fault orientation may have been controlled by zones of weakness in the crust inherited from the process of plate formation near the oceanic ridge. The orientation of transcurrent faults is thought to be similarly controlled within the southeastern corner of the Gorda plate off northern California (Wilson, 1986). Likewise, Aubouin and von Huene (1985) note that, where magnetic anomalies just seaward of a trench are less than 30° oblique to the trench axis, downward flexure of the oceanic plate is commonly accommodated by normal faults that parallel the magnetic anomalies rather than the trench.

Focal mechanisms of the M_S 6.9 and two M_S 7.6 shocks exhibit subhorizontal NW-SE-oriented T axes and NE-SW-oriented P axes. Allowing for the likelihood that the earthquakes occurred on preexisting zones of weakness, we infer that the minimum (tensional) and maximum (compressive) stresses are nearly horizontal and lie within the NW and NE quadrants, respectively. Thus the tensional stress axis is inferred to be directed toward the NE end of the 1964 rupture zone (Figure 1).

Globally, oceanic intraplate earthquakes often occur beneath or just seaward of the trench following large interplate thrusts. Nearly all such earthquakes involve normal faulting, with the inferred minimum principal stress axis oriented nearly orthogonal to the arc. The inferred stress field is commonly attributed to bending of the plate (Chapple and Forsyth, 1979), slab-pull forces, or a combination of the two (Spence, 1987); these stresses are enhanced following large interplate thrust earthquakes (Christensen and Ruff, 1983; Christensen and Ruff, 1988). The orientation of tensional stress inferred from the recent Gulf of Alaska events and the occurrence of these events about 24 years after the great 1964 shock are consistent with these global observations.

Why did the Gulf of Alaska events involve strike-slip faulting, which reflects subhorizontal compression within the NE quadrant, rather than the more common normal faulting? Christensen and Ruff (1988) have found that earthquakes with their compressional stress axes oriented approximately horizontal and perpendicular to the trench occur within oceanic plates seaward of strongly coupled subduction zones that have not recently slipped. Therefore, we hypothesize that seaward of a junction between slipped and locked plate boundary segments, shear stresses favoring strike-slip faulting will be induced (Figure 3). Based on a review of the mechanisms compiled by Christensen and Ruff (1988), only 18 large ($M_S > 7.0$) oceanic earthquakes are known to have occurred since 1963 near a trench axis, and only 3 of these have substantial strike-slip components. The first, the M_S 7.7 Sunda strike-slip shock (11/21/69), does not appear to be related to recent subduction zone events. However, the remaining two, the M_S 7.2 Solomon Islands (7/29/77) and the M_S 7.1 northern New Hebrides (11/28/85) events, are located near the junction between recently slipped and potentially locked or strongly coupled arc segments and have mechanisms consistent with this model. The former event occurred near the Woodlark rift zone and may represent motion on an active transform boundary.

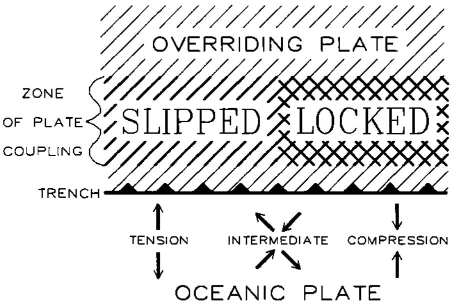

Fig. 3. Model of stress orientation in an oceanic plate seaward of a plate boundary. Normal faulting earthquakes commonly follow interplate thrust events and reflect episodic enhancement of tensional stresses induced by downdip slab pull. Outer-rise thrust earthqaukes seaward of a locked boundary segment indicate compressional stress normal to the boundary. Seaward of the junction between the slipped and locked plate boundary segments, shear stresses favoring strike-slip faulting will be induced.

The recent Gulf of Alaska shocks occurred seaward of the boundary between the 1964 rupture zone and the Yakataga seismic gap. Stresses may be particularly large here due to unusually high compressive stress inferred to be associated with oblique collision and subduction of the Yakutat terrane. Due to the orientation of the Fairweather fault, which strikes about 20° counterclockwise to the relative motion direction of the Pacific plate (Minster and Jordan, 1978), a small component of convergence begins at about 58°N and increases near 60°N where the northern boundary of the Yakutat terrane bends westward. East of the Dangerous River zone (DRZ, Figure 1), the Yakutat terrane is underlain by "continental" crust (Plafker, 1987), which is difficult to subduct. Accordingly, strong southwesterly directed compressional forces may radiate from the northeastern margin of the Yakutat terrane where continental blocks are colliding (Tapponier and Molnar, 1976).

Pacific-North American relative plate motion could be accommodated more efficiently than at present by decoupling the Yakutat terrane from the Pacific plate, thus completing the accretion of another terrane onto Alaska. One way to accomplish this would be to accelerate subduction along the Transition fault zone (Perez and Jacob, 1980). However, another model is suggested by the occurrence of these recent shocks. Slip on orthogonal faults, conspicuous cross-cutting seismicity, and significant seismicity off the main fault suggest extensive fragmentation of the Pacific plate south of the Transition fault zone. This fragmentation may be the initial step in developing a new transform and thrust boundary that will short circuit the current plate boundary. Three of the largest oceanic strike-slip events (1941 and 1975 North Atlantic and 1981 MacQuarie Ridge earthquakes) have occurred in transitional tectonic regimes (Lynnes and Ruff, 1985; Ruff and Cazenave, 1985).

The recent Gulf of Alaska earthquakes measurably perturbed the strain in the Yakataga seismic gap (Lisowski and Savage, 1988). In the eastern gap, near Icy Bay, strain relaxed by an amount equivalent to about 3-6 y of the accumulation measured since 1980 (Savage and Lisowski, 1988). In the central part of the gap, north of Cape Yakataga, there was a small decrease in the two-year rate of strain accumulation. The observed strain changes probably do not materially change expectations (Jacob, 1984) that a gap-filling shock may occur within the next few decades.

Given this recent seismicity, it is now clear that sizeable oceanic intraplate earthquakes are to be expected in the northeast Gulf of Alaska. These shocks can occur at least 250 km seaward of the Transition fault zone and involve a complex network of faults, such as those illuminated by the cross-cutting and off-fault seismicity that accompanied the recent earthquakes.

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