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TECTONIC MAP OF THE PUGET SOUND REGION, WASHINGTON, SHOWING LOCATIONS OF FAULTS, PRINCIPAL FOLDS AND LARGE-SCALE QUATERNARY DEFORMATION

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INTRODUCTION

The Puget Sound region is a seismically active area with hundreds of earthquakes occurring each year. Most of the earthquakes are so small that they can be detected only by the sensitive seismographs operated by the University of Washington (Crosson, 1974, 1975). Unfortunately not all have been small. Several damaging earthquakes have hit the area in historic time, but little is known about the geologic structures responsible for generating these earthquakes. Knowledge of the causative structures is fundamental to an adequate evaluation of the earthquake risks for the Puget Sound region.

Earthquakes are caused when stresses in the earth's crust are released by sudden movement along faults (see Explanation). This map is a compilation of known and inferred faults, and deformed deposits of Quaternary age (see geologic time relationships in figure 3). Most of the faults shown here are the result of tectonic forces that were active millions of years ago during early and middle Tertiary time and may not be related to the tectonic forces responsible for the current seismicity. The map shows what is known about the age of movement, but few of the faults have been studied in sufficient detail to establish whether they have been active or inactive in late Tertiary or Quaternary time. In addition, many of the earthquakes recorded in the Puget Sound region originated at depths of 40 to 60 kilometers and may not be related to structures exposed at the present land surface. Detailed geophysical and subsurface geologic studies may be required to discover the causative structures for these deep-focus earthquakes. However, evidence of faulting is insufficient by itself to assess earthquake damage potential because much damage occurs at a considerable distance from the fault-movement source, where earthquake intensity is related to local subsurface conditions or building construction rather than to proximity to the source.

Therefore, although the map is intended to assist planners, engineers, utility companies, public works agencies, and others concerned with land use, its major purpose is to provide a basis for the design of further detailed geologic and geophysical studies to understand better the structures responsible for generating earthquakes in the Puget Sound region.

The faults and other tectonic features shown on this map are compiled from previous work or were discovered or inferred through reconnaissance field studies and analysis of geophysical data consisting of aeromagnetic and gravity anomalies and high-resolution seismic profiles. The locations of the principal sources of information on bedrock structures are shown on figure 1, but in some instances modifications and additions have been made by the author. Faults are classified as to type of displacement and maximum age of the most recent movement. In addition, for the few faults that have been studied in detail, a minimum age of the most recent movement is also given. The location of deformed Quaternary deposits, including large-scale deformation such as faulting, folding, and tilting, are shown on the map and described in table 1. Only deformation which is considered to be of possible tectonic origin is shown. Soft-sediment deformation that could best be explained by glacial activity or features that appear to be related to slope failure are not shown. It should be recongized, however, that the forces resulting from the thick ice (up to 1.7 km) that overrode the Puget Sound Lowland several times during the Pleistocene epoch could have formed structures not readily distinguishable from those formed by tectonic deformation, and many of the deformed Quaternary deposits shown here may, in fact, owe their origin to causes other than tectonic activity.

Major structures inferred from interpretation of linear anomalies disclosed on gravity and aeromagnetic surveys are shown on the tectonic map and on figure 2. Those structures are described in table 2. Geophysical anomalies, however, may owe their origin to geologic processes other than faulting. Gravity anomalies result from juxtaposing rocks of differing density and thickness and magnetic anomalies result from juxtaposing rocks of different magnetic susceptibility. Such relationships, although commonly formed by faulting, can also be formed by steep folding or nontectonic means such as abrupt changes of lithologic facies (rock composition).

While the location of structures resulting from Cenozoic tectonic activity is the overall purpose of this map, older structures are also shown where mapped in the pre-Tertiary terranes of the San Juan Islands and the Northern Cascade Range.

Map users should keep in mind that fault lines on a map of this scale are not precisely located and should be used only as a guide for more detailed work in the field.

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Table 1.--*Localities of Quaternary deformation*

(Age of time and stratigraphic divisions are shown in figure 3)

Map number	Description of deformation	Age of deformed sediment	Reference [1]
1	Anticlinal fold in stratified clay and silt underlying undisturbed Vashon drift exposed in sea cliffs between Point Whitehorn and Neptune Beach. Limbs of fold dip 7°.	Pre-Fraser	Easterbrook, 1963
2	Anticlinal fold in probable glacial outwash deposits, interpreted from high resolution seismic profiles.	Pleistocene	Snavely and others, 1976
3	Tilted stratified clay and silt cut by numerous small normal faults with as much as 40 cm displacement.	Pre-Fraser	Fred Pessl, oral commun., 1977
4	Steep, up to 87°, south-dipping stratified clay, silt and iron-stained gravel exposed in valley of Tumwater Creek about 650 m south of Highway 101. Clay gouge at south end of exposure may be along inferred south-dipping thrust fault. To the north strata dip 10° south. Tilted strata are overlain by apparently undeformed Vashon drift.	Pre-Fraser	
5	Tilted stratified clay, silt, and sand dipping 13° south. Tilted strata appear to be overlain by undeformed Vashon Drift.	Pre-Fraser	
6	Overturned glacial drift in fault contact with Oligocene siltstone along south-dipping thrust fault exposed in roadcut on east side of Morse Creek.	Pre-Fraser	P.D. Snavely, Jr., oral commun., 1977

[1] Descriptions of deformation not referenced are the result of observations by the author during reconnaissance field studies

Map number	Description of deformation	Age of deformed sediment	Reference
7	Gentle arching of stratified Vashon glacial outwash along Swamp Creek anticline near mouth of Swamp Creek.	Post-Fraser	Brown and others, 1960
8	Normal fault striking N 50° W and dipping 68° NE. Offsets glacial outwash gravel and sand about 2 m, down on northeast side.	Post-Fraser ?	
9	Gentle arching of iron-stained gravel and sand overlain by undeformed outwash deposits of Fraser glaciation.	Pre-Fraser	
10	Marine seismic profiles between Point Wilson and Ebeys Landing on Whidbey Island show folding and possible faulting of Quaternary deposits.	Quaternary	Oceanographic Commission of Washington, 1975
11	Numerous normal faults and several gentle folds in stratified sand and silt exposed in lower part of sea cliff. Faults trend east-west and have displacements as much as 5.5 m. Limbs of folds dip up to 7°. Strata in upper part of sea cliff do not appear to have been deformed.	Pre-Fraser	
12	Stratified silt, clay, grit, and small pebble gravel tilted 55° SE, exposed in ditch along east side of road and overlain by undeformed glacial outwash.	Pre-Fraser	
13	Laminated to very thin-bedded silt and sandy gravel, and till dipping 52° N, exposed in roadcut 50 m north of Beaver Valley.	Pre-Fraser	
14	Thin-bedded, laminated silt, clay, sand, and iron-stained gravel striking N 30° W and dipping as much as 33° NE. Beds are contorted locally. Section cut by small high-angle reverse faults striking N 35° W and dipping 62° NE, east side upthrown about 30 cm.	Pre-Fraser	

Map number	Description of deformation	Age of deformed sediment	Reference
15	Peat, 15 cm thick, interbedded with clay, silt, and very fine-grained sand striking N 82° W and dipping 17° S.	Pre-Fraser	
16	Steeply dipping, up to vertical, glacial outwash gravels. May have been deformed by ice rather than by tectonic forces.	Pleistocene	
17	Stratified sand tilted 24° to the west and cut by several small faults with up to 30 cm displacement.	Pleistocene	
18	High-angle reverse fault exposed in trench. Cuts Salmon Springs drift. East side upthrown. Presence of scarp which presumably would have been obliterated by glaciation suggests some post-Fraser-glaciation movement.	Post-Fraser ?	Wilson, 1975
19	Saddle Mountain East fault, a high-angle reverse fault striking N 22° E, dipping 75° SE. In trench at locality 19 there is 3.5 m of apparent dip-slip displacement with Early to Middle Eocene Crescent Volcanics in fault contact with glacial drift. Movement along fault presumably raised the level of Price Lake and formed a small lake north of Saddle Mountain. Radiocarbon dating of stumps of drowned trees in Price Lake and the small lake to the north yielded ages of 1315$\pm$80 yr B.P. and 1155$\pm$85 yr B.P., respectively.	Holocene	Wilson, 1975; Carson, 1973
20	High-angle reverse fault. In trench at locality 20, fault strikes N 50° W, and dips 59° NE and appears to offset Salmon Springs drift 1.7 m.	Pre-Fraser	Wilson, 1975; Carson and Wilson, 1974
21	1100 m long linear "rift" valley that may have been formed by Late Quaternary fault.	Fraser or Holocene	Carson and Wilson, 1974; Wilson, 1975

Map number	Description of deformation	Age of deformed sediment	Reference
22	Folded stratified Salmon Springs drift, including varved lacustrine silt and clay. Limbs of folds dip up to 42°.	Pre-Fraser or younger	
23	Apparent movement along fault during earthquake in 1948. This may have been landsliding rather than tectonic movement along the fault.	Historic ?	Pease and Hoover, 1957
24	Possible fault scarp on botton of Puget Sound off the Nisqually Delta associated with magnetic anomaly.	Holocene ?	Univ. of Washington, Dept. of Geol. Sci., Unpubl. report on the Nisqually Delta.
25	Faulted and slightly tilted gravel at east end of Fox Island.	Pre-Fraser	Bretz, 1913, p. 227
26	Folded pre-Salmon Springs drift cut by many normal faults with displacements up to 0.6 m. Limbs of folds dip up to 38°. Overlying Vashon? drift is not deformed.	Pre-Fraser	Smith, 1972
27	Steeply dipping "fault" contact between sheared clay on the east and crossbedded sand on the west. Strike of contact varies from N 10° E to N 70° W. Dip of sand steepens due to drag along contact. Interpreted as diapiric intrusion of clay into sand. Overlying Vashon? drift appears to be undeformed.	Pre-Fraser	
28	North-trending fault in Vashon drift. Apparent scarp suggests possible Holocene movement. Vertical displacement estimated to be 6 to 9 m.	Holocene ?	Allan Fiksdal, oral commun., 1977
29	Salmon Springs drift and Puyallup Formation in fault contact along nearly vertical NE-trending fault, downdropped on the NW.	Pre-Fraser	Waldron, 1961

Map number	Description of deformation	Age of deformed sediment	References
30	Several normal faults in Vashon drift striking N 40° E and dipping northwest. Displacements are all less than 65 m.	Fraser	Waldron, 1961
31	Fault in Salmon Springs drift in NE ¼ sec. 14. Downthrown on north. Amount of displacement is unknown, but is believed to be no more than a few tens of feet.	Pre-Fraser or younger	Waldron, 1961
32	In sea bluff exposures in N ½ sec. 29, south of Saltwater State Park, Salmon Springs lacustrine sediments dip about 14° north.	Pre-Fraser or younger	Waldron, 1961
33	Northwest-striking, nearly vertical, normal fault exposed in bluff at northwest outskirts of Sumner. Vashon drift has been downdropped about 24 m on the southwest.	Fraser	Crandell, 1963
34	Two faults exposed in the valley of Kings Creek in the SW ¼ sec. 34 offset the Lily Creek Formation. One fault strikes N 60° W and dips 50° SW. The other strikes N 5° E and dips 55° W. Both faults have plastic clay gouge zones 15 cm to 60 cm wide.	Pre-Fraser	Crandell, 1963
35	Prominent lineation identified by photointerpretation and field investigations may be fault-related to July 1973 earthquake and aftershocks.	Holocene ?	Crosson and Frank, 1975
36	Near-vertical north-trending fault in Orting? glaciolacustrine and fluvial sediments. East side downdropped about 9 m.	Pre-Fraser	Mullineaux, 1970
37	Uplifted shallow-water marine sand and gravel deposits containing mollusks and some wood. Mollusk shells collected 4.9 m above present sea level yielded radiocarbon date of 3260±80 B.P. Wood from about 2.4 m above sea level was radiocarbon-dated at 4530±90 B.P.	Holocene (3260±80 B.P.)	
38	Sand in Magnolia Bluff is "somewhat bowed up" just south of West Point.	Pre-Fraser	Bretz, 1913, p. 227

Table 2.--*Structures inferred from interpretation of linear geophysical anomalies.*

Structures are shown on the tectonic map and figure 2

Inferred structure	Description	Reference
A	Southern boundary of a high amplitude magnetic anomaly. Considered to be the westward continuation of the Devils Mountain fault separating highly magnetic ophiolite on the north from weakly magnetic metamorphic rocks on the south. Youthful appearance of topographic lineations along the fault west of Lake Cavanaugh suggest that this structure may have been active in late Quaternary time; however, no geologic units younger than Oligocene? are definitely known to have been offset by the Devils Mountain fault.	U.S.G.S., 1977; J.T. Whetten, oral commun., 1977
B	Sharp east-trending gravity nose bounding the north side of a large gravity low to the southeast. Coincides with linear alignment of series of small magnetic lows that may be related to the inferred fault zone. This anomaly appears to bound pre-Tertiary metamorphic rocks at or near the surface on northern Whidbey Island from a thick section of unconsolidated Quaternary deposits on the south. It may also form the northern boundary of a basin of Tertiary sedimentary rocks to the south. Deformed Quaternary sediments (Locality 3) occur along the strike of this inferred structure.	U.S.G.S., 1977; Rogers, 1970; Macleod and others, 1977

Inferred structure	Description	Reference
C and D	A pronounced linear magnetic high extending southeast from near Victoria on Vancouver Island. Has been interpreted as a northeast-dipping slab of lower to middle Eocene Metchosin (Crescent) Volcanics bounded on both sides by faults (structures C and D). MacLeod and others (1977) consider C to be the offshore continuation of the Leech River fault of Vancouver Island.	MacLeod and others, 1977
E	Northeast side of linear magnetic anomaly probably reflecting a fault in early to middle Eocene basement rocks.	MacLeod and others, 1977
F	Northern edge of a high amplitude magnetic anomaly bounding Eocene volcanic rocks on the south from Tertiary sedimentary rocks on the north. Interpreted as possible fault with the north side down.	MacLeod and others, 1977; U.S.G.S., 1977
G	Northeast side of linear magnetic high and southern boundary of a pronounced gravity low. Interpreted as possible northwest-trending fault. Deformed Quaternary sediments (map locality 11) occur along the strike of this inferred structure.	U.S.G.S., 1974, 1977; Rogers, 1970
H	An inferred east-trending fault or monoclinal fold bounding a gravity high on the north from the major gravity low at Seattle.	Rogers, 1970
I	The anomaly associated with this feature is one of the largest gravity anomalies in the United States and is interpreted as a major fault zone, down to the north. It also coincides with the northern boundary of a large magnetic high and is associated with steeply dipping Tertiary strata. Daneš and others (1965) calculated a total of about 11 km of displacement along two parallel faults to account for this large gravity anomaly. It has been estimated that the area to the	Rogers, 1970; Daneš and others, 1965; U.S.G.S., 1974, 1977; Hall and Othberg, 1974.

Inferred structure	Description	Reference
I (cont.)	north of this structure is underlain by more than 1100 m of unconsolidated deposits, suggesting possible large movements during the Quaternary. In addition, at map locality 37, immediately south of the structure, uplifted shallow water marine deposits indicate more than 4.9 m of uplift along this structure in past few thousand years. The position of the structure shown on the tectonic map and on figure 2 is drawn north of steeply dipping Oligocene sedimentary rocks on Bainbridge Island and Eocene coal-bearing strata in the Reynolds mine north of Issaquah. However, as suggested by Daneš and others (1965) the anomaly may represent movement on more than one fault located farther to the south.	
J	Eastern boundary of a northeast-trending gravity high underlain by thick, steeply dipping section of Crescent Volcanics. This may be fault against which the east-west structures H and I terminate.	Daneš and others, 1965
K	Southern boundary of pronounced gravity and magnetic highs. Interpreted as fault or steep monoclinal fold, down to the south.	Daneš and others, 1965; Rogers, 1970; U.S.G.S., 1974, 1977
L	Northeast side of prominent northwest-trending positive gravity anomaly. May represent contact of oceanic basalts of the early to middle Eocene Crescent Volcanics with lower density continental crust to northeast. May be overlapped by younger Tertiary formations.	Daneš and others, 1965

1. Abbott, 1953
2. Allison, 1959
3. Bethel, 1951
4. Brown and others, 1960
5. Bryent, 1955
6. Buckovic, 1974
7. Cheney, written commun., 1976
8. Crowder and others, 1966
9. Danner, 1957
10. Dobrin, M. B., written commun., 1975
11. Dungan, 1974
12. Ellingson, 1959
13. Ellis, 1959
14. Fisher, 1970
15. Fisher, 1957
16. Fiske and others, 1963
17. Foster, 1960
18. Fulmer, 1975
19. Gard, 1968
20. Glassley, 1974
21. Gower and Wanek, 1963
22. Grant, 1966
23. Hammond, 1963
24. Hartman, 1973
25. Heath, 1971
26. Jones, 1959
27. Kremer, 1959
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44. Vance, 1975
45. VanDiver, 1964
46. Vine, 1962
47. Waldren, 1962
48. Warren and others, 1945
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51. Wiebe, 1968
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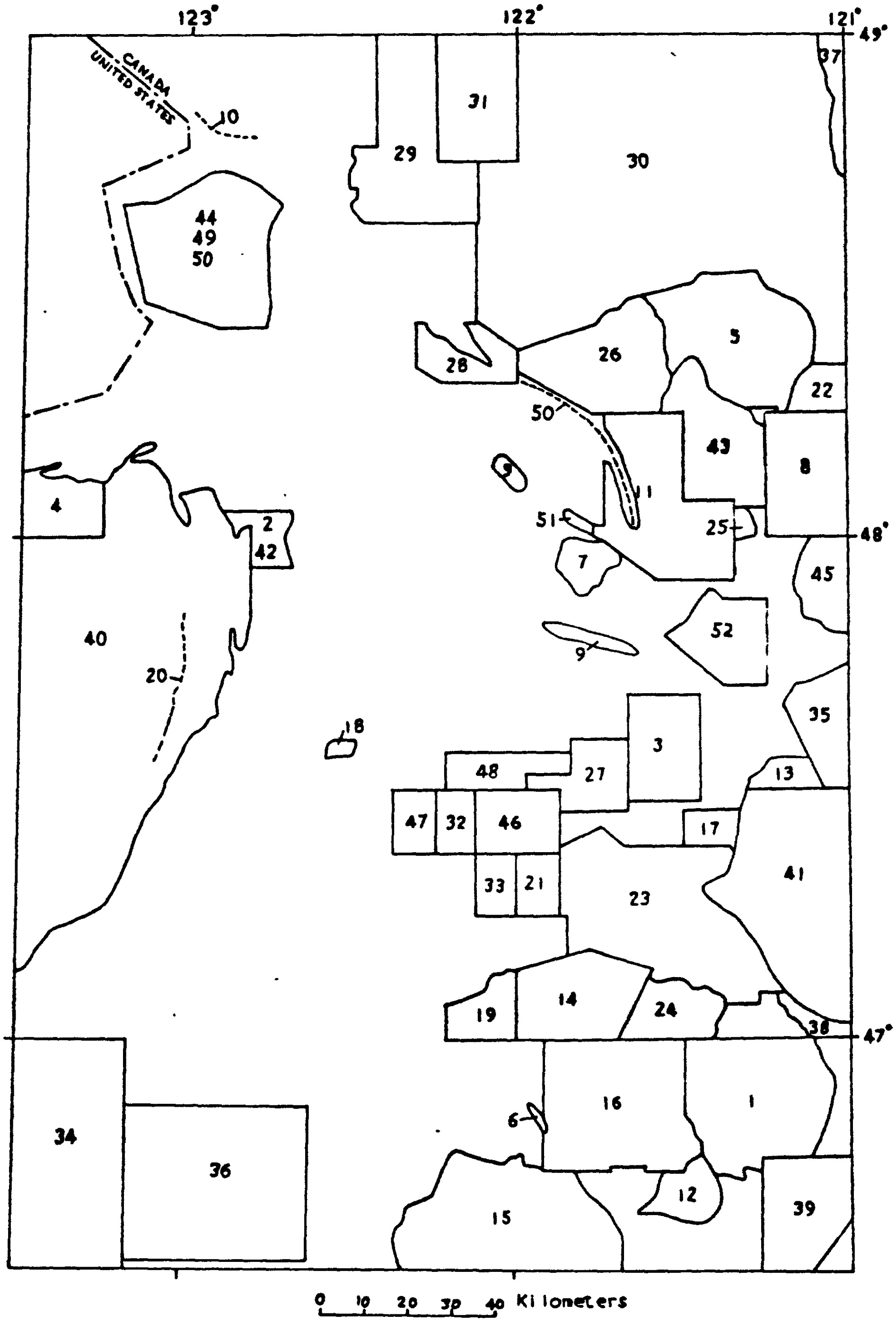


Figure 1.--Index of principal sources of bedrock structures

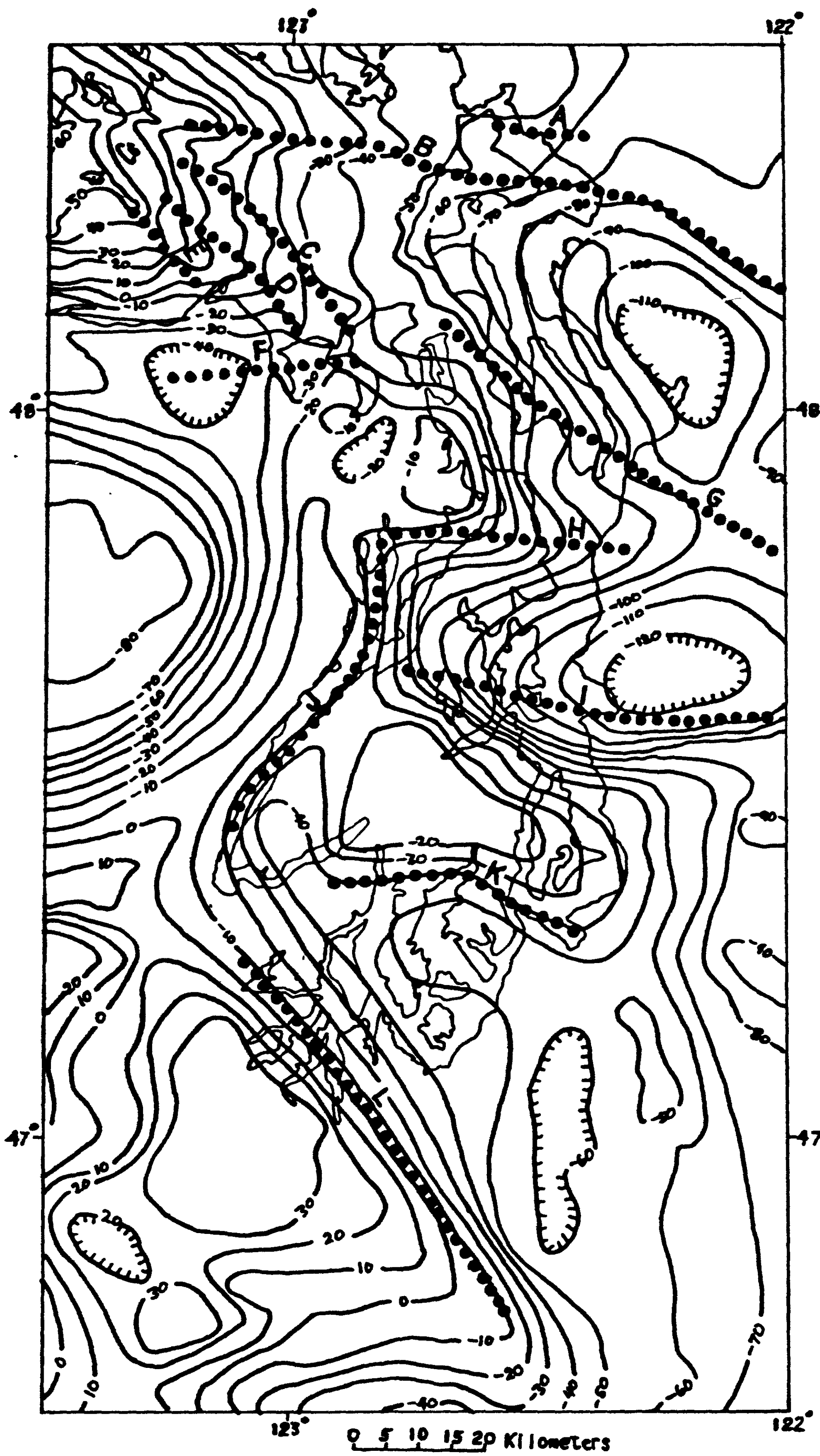
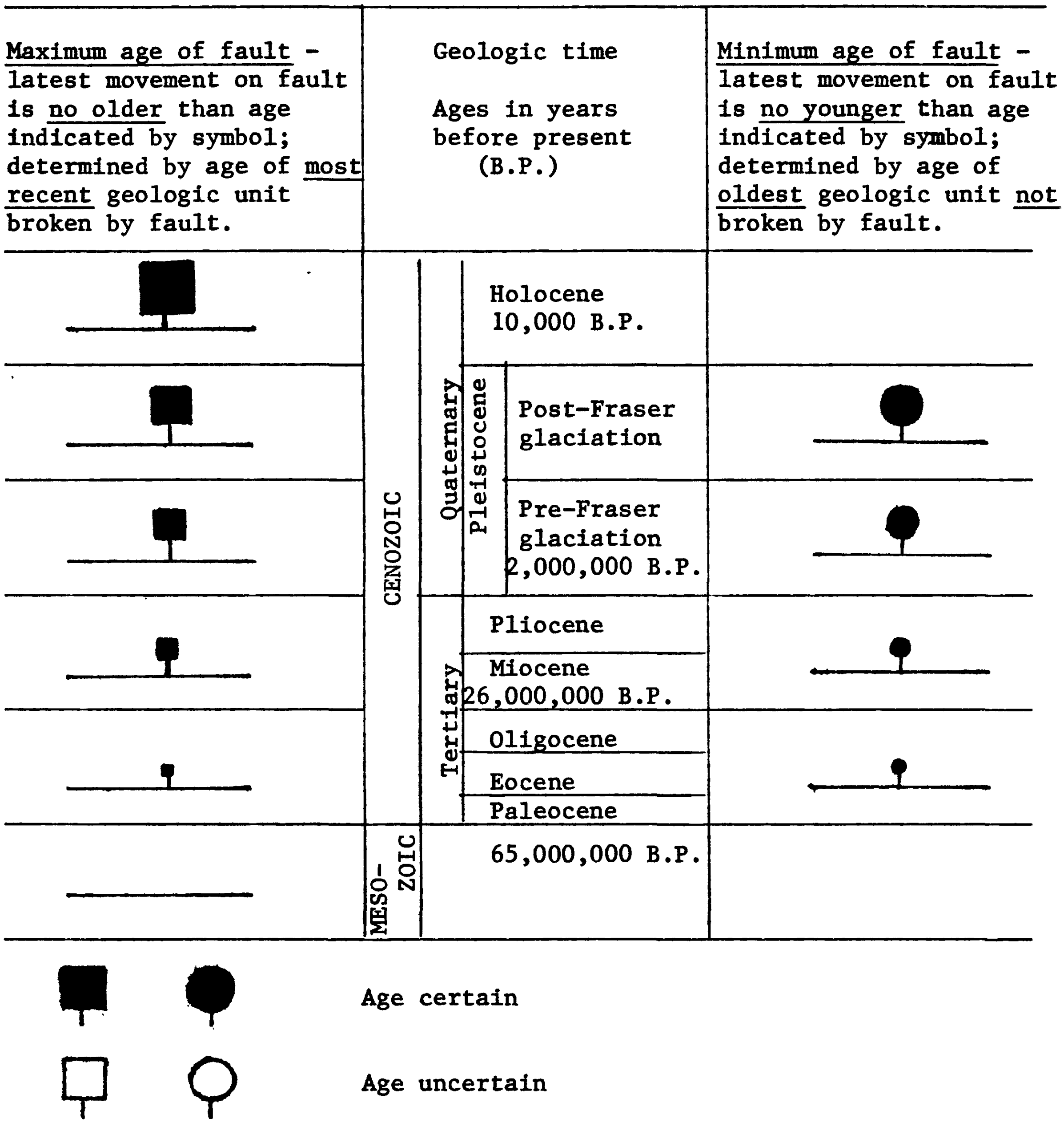
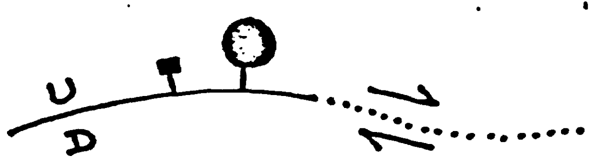


Figure 2.--Regional gravity map and inferred structures. Contours in milligals. Modified from MacLeod and others (1977), Rogers (1970), and Bonini and others (1974).

Figure 3. SYMBOLS FOR AGE OF FAULTING

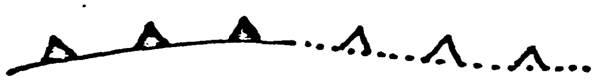


EXPLANATION



Fault

Fracture surface or zone along which the rocks on either side have moved relative to one another; dotted where covered or inferred. U, relatively upthrown side; D, relatively downthrown side. Arrows indicate horizontal direction of relative movement. Square or circle shows how recently movement occurred on fault (see Fig. 3 "SYMBOLS FOR AGE OF FAULTING").

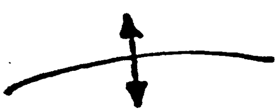


Thrust fault

Inclined low angle fracture surface along which the rocks above the fracture have moved upslope with respect to those beneath; dotted where covered or inferred. Sawteeth on upper plate.

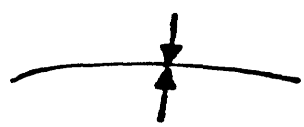
Inferred structure

Inferred from gravity, aeromagnetic or marine seismic studies. May represent sharp fold or abrupt change in rock composition (lithology) rather than fault. U, relatively upthrown side; D, relatively downthrown side. Arrows indicate horizontal direction of relative movement.



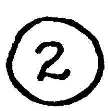
Anticline

A folded rock structure, convex upward.



Syncline

A folded rock structure, concave upward.



Location of Quaternary deformation

Folds and faults, no older than Quaternary age. Number refers to Table 1.