Tectonomagmatic Evolution

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Introduction

The Oslo Graben is part of an intracontinental rift zone characterized by an impressive suite of alkaline intrusive and extrusive rocks. These rocks, which cover more than 75% (or about 6500 km^2) of the present graben 'floor', are intimately related to the tectonic evolution of the area. Until recently the bulk of the igneous rocks were believed to have formed during a relatively short time span at the presumed climax of the taphrogenesis in Lower Permian time (Holtedahl 1935, 1943, Barth 1945, 1954, Oftedahl 1960, 1967, Heier & Compston 1969). In general, this thesis seems to hold. However, new studies of the igneous rocks have produced a mass of data that make it possible to piece together a more detailed, if still tentative, tectonomagmatic model of the rift.

The view has evolved in recent years that intracontinental rifting occurs as the incipient stage of an evolutionary process normally ending with oceanic rifting and spreading. The continued existence of some continental paleorifts, however, testifies that the assumed process is sometimes aborted or that continental rifting may take place in pulses. Several continental rifts show evidence of repeated tectonic and volcanic activity. These pulses probably reflect the geodynamic evolution of the individual tectonic regime. For the Oslo paleorift there is at least some evidence of a prolonged period of episodic tensional faulting which may be related to movements in the North Atlantic region. Evidence for this relationship will be briefly reviewed with particular emphasis on the tectonic and volcanic evolution of the main graben-forming period that began in Permo–Carboniferous time.

Precursors

The crystalline Precambrian terrain surrounding the Oslo Region is criss-crossed by a number of faults, joints and mylonite belts (Plate 2) that have characteristic directional trends (Fig. 1a & c) (Ramberg et al. 1977). These trends also occur within the Oslo Region, although north-trending fractures clearly predominate (Fig. 1b). The rocks in many of the mylonite belts and graben boundary faults are blastomylonites with clear evidence of repeated fragmentation (e.g. Brøgger 1886, Bugge 1928, 1965, Holtedahl 1943, Gleditsch 1952, Skjeseth 1963, Bjørlykke 1966, Morton et al. 1970, Naterstad 1971).

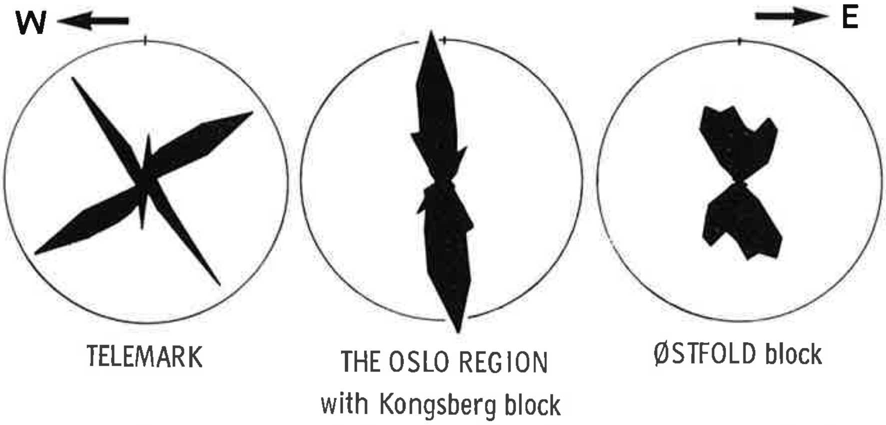


Fig. 1. Distribution diagram of fractures from the Oslo Region and its vicinity (Figure redrawn from Ramberg et al. 1977).
a. The Precambrian Telemark area (west of the Oslo Region).
b. The Oslo Region proper (including the Kongsberg block).
c. The Precambrian east of the Oslo Region (mainly the Østfold block).
The N–S direction is distinct in the Oslo Region and the gridded pattern is distinct west and east of the Oslo Region. Note that the areas east of the Oslo Region have more N–S fractures than the area west of the region.

The pre-existing pattern of predominantly joints, shear faults and breccias was to some extent and in localized zones rejuvenated during the Late Paleozoic and Mesozoic times when the area entered into a prolonged period of tensional deformation and fault-block movement.

Stratigraphic and lithologic studies have revealed that the Permian graben formation was preceded by the formation of narrow sedimentary troughs (aulacogens) in Early Cambrian, Middle Ordovician and especially Upper Silurian times (Henningsmoen 1952, Skjeseth 1952, Spjeldnæs 1955, Størmer 1967). There is some evidence of brittle deformation and fault topography during these early stages of trough formation. Immediately to the north of the Oslo Graben, a major fault-bounded sedimentary trough of several thousand metre's thickness, the Late Precambrian to Early Cambrian 'Sparagmite Basin' (Bjørlykke et al. 1976) or 'Østerdal Aulacogen' of Roberts & Gale (1977), trends towards NNW to N and contains local effusions of alkali basalt (Bjørlykke 1969, pers. comm. 1977, Nystuen pers. comm. 1977). The major faults bordering this basin may have been the sites of later Permian displacement. The basin, therefore, marks a possible precursor as well as a continuation of the Oslo Rift, although an alternate trend could be to the NNE along the axial extension of the pronounced Oslo gravity high (Ramberg 1973, 1976). This latter direction also contains the Särna alkaline complex of Permian age (Bylund & Patchett 1977) further towards the NNE in Sweden.

At the conclusion of the formation of the 'Sparagmite Basin', alkaline igneous activity took place in an area centered at the Fen complex (Brøgger 1921, Sæther 1957, Ramberg 1973) some 12 km SW of the Oslo Region. Together with a number of Permian gabbroic volcanic necks ('Oslo-essexites') and breccias as well as Precambrian mafic intrusions near Kongsberg and Tyrifjorden (Ramberg 1976), the Fen complex is located on a line that closely coincides with the NNE-trending western border of the Oslo Region. Still further to the SSW this trend coincides with a line through the Permo–Carboniferous ultramafic neck (Touret 1970) at Vegårdshei, on the 'Great Friction Breccia', as well as the (Permian?) intrusive complex outside Kristiansand (Åm 1973). Thus, this major tectonic zone parallel to the overall axis of the Oslo Graben evidently served as an avenue of ascent for both Permian volcanic necks and older intrusives of alkaline kindred.

Main taphrogenetic event — volcanic products

The formation of the Oslo Graben began and culminated in the Permian (or Carbo–Triassic) with the development of extensional tectonics, volcanism and major subsidence. The volcanic rocks (mainly basalts and rhomb porphyry lavas), together with the plutonic and subvolcanic rocks (larvikite, nordmarkite, syenites, nepheline syenites, granites and gabbroic rocks of the 'Oslo-essexite' series) reflect a magmatic and tectonic evolution which possibly classify the Oslo Region as an arch-volcanic epi-platform rift zone (Milanovsky 1972). The *volcanic* products can roughly be classified as mafic (basaltic lava, B), intermediate (rhomb porphyry lava, RP) and felsic (trachytes and alkali rhyolites, T, R). The detailed stratigraphy of the lava flows was first worked out for the Krokskogen lava plateau by Brøgger, Schetelig and co-workers in the period 1910–1917. Since then stratigraphic sequences from a number of areas have been presented by Sæther (1946, 1962) and Oftedahl (1952, 1960, 1967), see Table 1. Oftedahl (1960) divided the eruptions into three phases: An initial phase and a possible concluding phase of fissure eruptions (flood lava stages) separated by a period of central volcanism, cauldron subsidence and explosive eruptions.

The volcanics presently cover about 1500 km^2, and are found primarily in four different geological environments:

(1) The *Skien* basalt area, situated to the far south (Plate 1), is built up of exclusively (B_1) basaltic flows forming a sequence that may be close to 2 km thick (Ramberg 1976, Segalstad 1976). The Skien basalts are presumably linked to early fissure eruptions, and are presently interpreted as a stratoid trap series deposited just outside incipient boundary faults that were later concealed by intrusives.

(2) The *Jeløya* volcanics occur in the southeast, on the island Jeløya close to the Oslofjord master fault. These consist of a thick (ca. 1200 m) B_1 sequence and several rhomb-porphyry flows. The whole sequences is dominated by tuffs and volcanic breccias, agglomerates and debris flows (Plate 5). Together with the rhomb-porphyry conglomerate (fanglomerate) on the islands further to the south (see Larsen et al. this volume), the Jeløya volcanics are part of an

Table 1. Stratigraphy of volcanic rocks of the Oslo Graben as given by Oftedahl (1960). Horizontal lines separate the three subsequent eruptive phases proposed by Oftedahl. B_1 etc.-basalts. 1, 2,3, etc.-rhomb porphyries. Lava areas: Kr – Krokskogen. Ni – Nittedal. Ve – Vestfold. Cauldrons: Ø – Øyangen. B – Bærum. A – Alnsjø. D – Drammen. G – Glitrevann. S – Sande.

Kr	Ni	Ø	B	A	D	G	S	Ve
		B_5						17
		17						Trach.
		16		Lava cgl.				16
		15						15
			B_4(?)	Argillite				B_4
		14			14	14		14 a, b, c
		13		Agglom. of 13 and acid. volc.	13	13		13
			12 a, b, c,			Welded agglom.		
			Tuffs, aggl. with ignim.	Trachyte Tuff		Rhyolitic dome	Agglom.	
			B_3		B_3	B_3	etc.	B_3
			Ignimbrite	Agglom.	Rhyolitic crystal tuff	Rhyolite (ignimbr.)		Trachytic ignim.
B_3	B_3(?)		B_3	B_3	B_3	B_3		
12								12
11			11		11	11		11
B_2+10					B_2	B_2		
9	9				9	9	9(?)	9
8	8				8	8		8
7	7				7	7	7	7
6	6				5+6	6	6	6 a, b
5	5					5	5	5 a, b
4 a, b	4				4	4	4	4 a, b, c, d
3 a, b							3(?)	
2 a, b	2				2	2	2	2 a, b
1	1				1	1	1	1
B_1	B_1				B_1	B_1	B_1	B_1

elongate eastern province with characteristic features reflecting its proximity both to local volcanic vents as well as to the main Oslofjord fault.

(3) The *Krokskogen* and the *Vestfold* lava plateaus are found in the central and southern parts of the Oslo Region, respectively (Plate 1). Both consist of rhomb porphyry lavas, with occasional basalts and trachytes (lavas and ignimbrites). The lower part of the succession is commonly interpreted as flood volcanics and/or products of large shield volcanoes. Vestfold is the most extensive lava area in the Oslo Region; the original thickness may have been more than 3 km (Oftedahl 1967, pers. comm. 1975). In the Krokskogen area, the lava thickness possibly exceeds 1.5 km. The lower kilometre or so of the sequence represents the classical series where Brøgger first demonstrated the lava stratigraphy.

(4) The *cauldrons*, of which at least 12 can be recognized (Holtedahl 1943, Oftedahl 1953, 1967, Naterstad 1971, Sørensen 1975, Segalstad 1975, Larsen,

unpublished data), contain predominantly basalts, presumably representing the central volcanic stage, and felsic volcanics (trachytes and alkali rhyolite ignimbrites) representing the subsidence and caldera filling stage. The volcanics are commonly associated with subvolcanic trachytic or quartz porphyritic central domes, with composition often similar to that of the ring dike of the same cauldron.

The volcanics of the Vestfold and Krokskogen areas and particularly the Skien area represent the lower part of the stratigraphical sequence whereas the cauldron volcanics include the higher parts. Basalts and felsic volcanics of the cauldron complexes interfinger with the upper flood lavas (RP), clearly indicating that the flood (or plateau) lava stage did not unphase before the onset of the central volcano/cauldron subsidence stage.

Today, only remnants of the original lava sequence occur. Including the new data on the thick Skien basalts (Ramberg 1976, Table 14), the present lava volume totals about 500 km^3. The original volcanic cover exceeded the graben area perhaps by as much as a factor of two. This estimate considers basic and rhomb porphyry dikes far outside the boundaries of the Oslo Region (see e.g. Oftedahl 1952, fig. 17) as well as various volcanic inclusions in explosion breccias up to 30 km west of the region (Brøgger 1931) and rhomb porphyry fanglomerates along the eroded Oslofjord fault scarp (Størmer 1935). Assuming only moderate average lava thicknesses, the original lava volume probably greatly exceeded 10,000 km^3 (Oftedahl 1952, Ramberg 1976).

The *present* volume proportions of the volcanic rocks are approximately 55% basalts, 35% rhomb porphyries and 10% felsic rocks. These numbers contrast with the *areal* frequency of outcrops of *plutonic* rocks (Barth 1945, 1954) which shows a marked preponderance of rocks of intermediate and felsic composition. However, *volume* frequency distribution based on mass calculations from gravity data (Ramberg 1976, fig. 79) reveals a striking preponderance of mafic/ultramafic plutonic rocks, more in harmony with the proportions found for the somewhat accidental remnants of the volcanic rocks.

The various rhomb porphyry units (RP_1, RP_2, etc.) are often thick (up to 100 m or more), quite extensive and commonly composed of a small number of individual flows. The units, which are rather similar in appearance, can be distinguished mainly by the amount, shape and size of the phenocrysts anorthoclase–plagioclase). The first rhomb porphyry unit, RP_1, is missing in the southwest (Skrim area) where the RP_2 follows directly on top of a 350 m thick pile of B_1 basalts (Rohr-Torp 1973) (see Fig. 4). Chemically, the porphyries are homogeneous both in major and trace element contents, with SiO_2 around 56% and total alkalies about 9%. (For chemical analyses of Oslo lavas, see Table 2; and Neumann, this volume). The rhomb porphyry lavas are rich in trace elements such as REE, Zr, Hf, Sr, Rb, Th and U. The average initial Sr^{87}/Sr^{86} ratio is 0.7040 (Sundvoll, pers. comm. 1976). From plagioclase thermometry of the phenocrysts (Kudo & Weill 1970) and a Eu--anomaly of distribution coefficients of phenocryst/matrix (Weill & Drake

Table 2. Chemical analyses and katanorm calculations of Oslo volcanics. (From Weigand 1975, Brøgger 1933a, Holtedahl 1943, and unpublished data from the authors.) Norm calculation using standard Fe_2O_3 values and on a CO_2- and H_2O-free basis. The basalts are average analyses, number of samples in parentheses.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	43.60	45.55	46.45	48.19	49.97	50.05	44.90	49.60	49.68	53.51	52.00	55.26	63.56	63.27	75.44
TiO_2	3.39	2.97	2.77	2.85	2.97	2.63	4.24	2.76	3.00	1.25	2.59	1.14	1.08	0.59	0.07
Al_2O_3	11.77	13.80	11.60	14.29	13.83	13.70	13.25	17.30	16.06	18.38	14.67	19.64	15.04	16.88	12.33
Fe_2O_3	6.74	6.35	6.00	7.19	6.63	6.86	7.95	7.00	8.34	7.92	10.20	4.53	6.75	1.47	0.49
FeO	6.59	6.20	6.45	5.06	4.97	6.75	5.90	4.68	3.70	0.97	1.86	2.20	0.39	2.63	1.00
MnO	0.18	0.18	0.20	0.21	0.19	0.20	0.24	0.16	0.22	0.28	0.32	0.30	0.13	0.03	0.11
MgO	7.77	6.28	10.17	6.22	4.11	5.53	7.80	4.08	4.62	1.34	2.38	1.10	0.60	1.84	0.52
CaO	12.35	10.01	10.05	8.95	6.35	9.00	10.67	7.94	7.66	5.07	5.20	6.83	0.70	2.98	0.01
Na_2O	2.39	3.22	2.50	3.69	4.07	2.35	3.38	3.98	3.46	4.68	3.60	4.16	3.30	2.68	2.38
K_2O	2.04	2.30	2.70	2.26	3.58	0.72	1.52	1.41	2.04	4.29	3.85	2.69	6.73	6.80	7.13
P_2O_5	(0.70)	(0.70)	0.52	0.45	0.43	0.41	0.84	0.39	0.50	0.71	1.05	1.40	0.22	0.31	0.01
Sum	96.82	96.86	99.41	99.36	97.10	98.20	100.69	99.30	99.28	98.40	97.72	99.55	98.50	99.48	99.49
KATANORM															
Q	–	–	–	–	–	6.45	–	–	0.30	–	2.93	6.36	16.01	11.37	31.02
C	–	–	–	–	–	–	–	–	–	–	–	0.91	1.79	0.48	0.78
OR	12.58	14.10	16.10	13.56	22.05	4.46	9.05	8.50	12.36	25.89	23.92	16.12	41.11	40.53	42.98
AB	9.67	19.28	13.32	26.40	33.89	22.15	20.62	36.46	31.87	40.46	34.00	37.90	30.64	24.28	21.81
AN	16.05	17.04	12.59	16.02	9.28	25.95	16.64	25.70	22.85	16.84	13.16	25.10	2.10	12.87	–
NE	7.64	6.44	5.61	4.35	2.53	–	5.99	–	–	1.48	–	–	–	–	–
HY	–	–	–	–	–	17.23	–	8.05	12.20	–	9.98	6.21	1.92	7.42	2.77
DI	34.52	23.81	27.46	20.89	16.51	14.49	24.96	9.51	10.22	3.29	5.41	–	–	–	–
OL	7.73	8.66	15.43	9.17	5.62	–	8.96	2.47	–	5.81	–	–	–	–	–
MT	5.34	4.85	4.51	4.62	4.87	4.53	6.05	4.54	4.82	2.94	4.50	2.80	–	1.55	0.52
HM	–	–	–	–	–	–	–	–	–	–	–	–	4.86	–	–
IL	4.93	4.30	3.90	4.03	4.32	3.85	5.96	3.92	4.29	1.78	3.80	1.61	0.62	0.83	0.10
AP	(1.53)	(1.52)	1.10	0.96	0.94	0.90	1.77	0.83	1.07	1.52	2.31	2.97	0.48	0.65	0.02
D.I.	29.89	39.82	35.03	44.31	58.47	33.06	35.66	44.96	44.23	67.83	60.85	67.35	87.76	76.18	95.81

1. B_1 pyroxene basalts from Skien (3). 2. B_1 plagioclase–pyroxene basalts from Skien (2). 3. B_1 pyroxene basalts from Vestfold (2). 4. B_1 plagioclase–pyroxene basalts from Vestfold (7). 5. B_1 plagioclase–pyroxene basalts from Jeløy (3). 6. B_1 aphyric basalts from Krokskogen (8). 7. B_2 pyroxene basalts from Krokskogen (2). 8. B_3 plagioclase basalts from Glitrevann cauldron (4). 9. B_3 plagioclase basalts from Bærum cauldron (5). 10. Rhomb porphyry (RP_1), Kolsås, Bærum. Brøgger 1933a, p. 68. 11. Rectangel porphyry (RP_{13a}) Pipenhus, Sørkedalen. Brøgger 1933a, p. 70. 12. Rectangle porphyry (RP_{13c}) Bergendal, Sørkedalen. Brøgger 1933a, p. 70. 13. Trachytic tuff, Sloravann, Sørkedalen. Holtedahl 1943, p. 64. 14. Ignimbrite, Lathusåsen, Bærum. Holtedahl 1943, p. 64. 15. Rhyolite crystal tuff, Bragernesåsen, Drammen. Brøgger 1933a, p. 108.

1973) the approximate equilibrium temperature of the feldspar phenocrysts is about 1100°C and $f_{O_2} \approx 10^{-8}$ atm (Larsen 1975). These estimates fit well with the starting equilibrium temperature and oxygen fugacity calculated for the monzonitic (larvikite) rocks (Neumann 1976). Chondrite-normalized REE diagrams for the rhomb porphyry lavas and larvikites are almost identical. The only significant difference is a tendency toward a weak positive Eu-anomaly in the larvikites and a weak negative anomaly in the rhomb porphyries, a phenomenon which is tentatively interpreted as a cumulate feldspar effect in the subvolcanic larvikites and the associated residual effect in the extruded rhomb porphyry lavas (Larsen 1975).

Taken together, the mineralogical and geochemical data support the earlier notion that the larvikites and kjelsåsites represent plutonic (to subvolcanic)

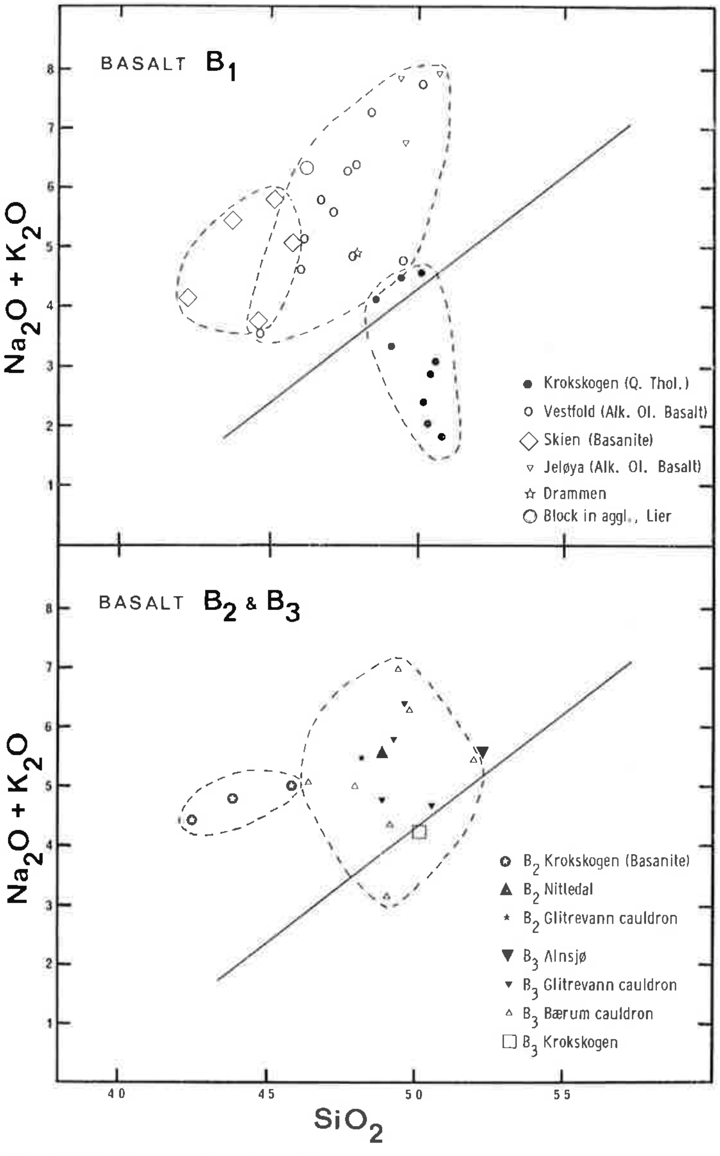


Fig. 2. SiO_2 – Na_2O+K_2O diagram for the Oslo Region basalts (mainly after Weigand 1975). Hawaii dividing line after MacDonald & Katsura 1964.

equivalents of the rhomb porphyry lavas, and that the larvikites must have crystallized in shallow magma chambers (Neumann, this volume). The relatively constant and low Th/U ratio of the larvikites (Raade 1973) implies a deep, possibly mantle origin. The same conclusion consequently applies to the rhomb porphyry lavas which have the same ratio but a slightly higher total (Th + U) content.

Quite contrary to the uniform rhomb porphyry lavas, the early *basalt* flows, have varied petrological and chemical composition (Fig. 2). Volcanism in the

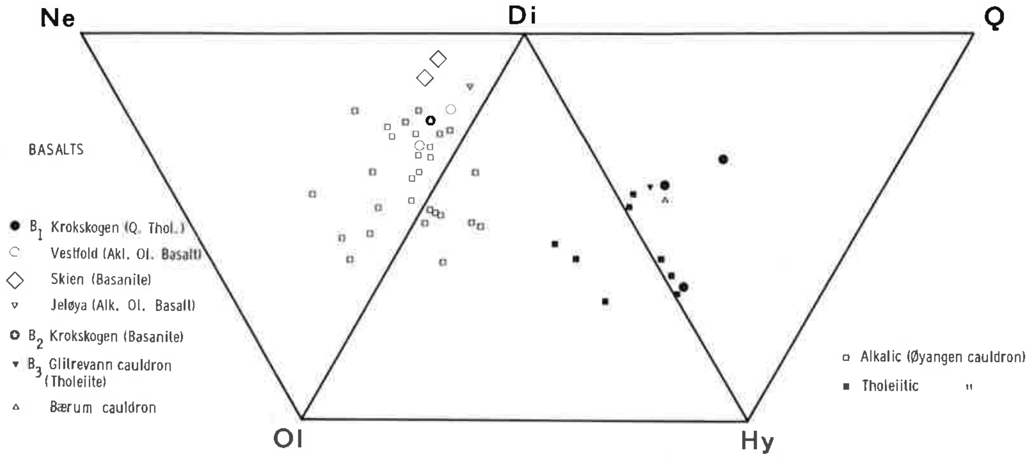


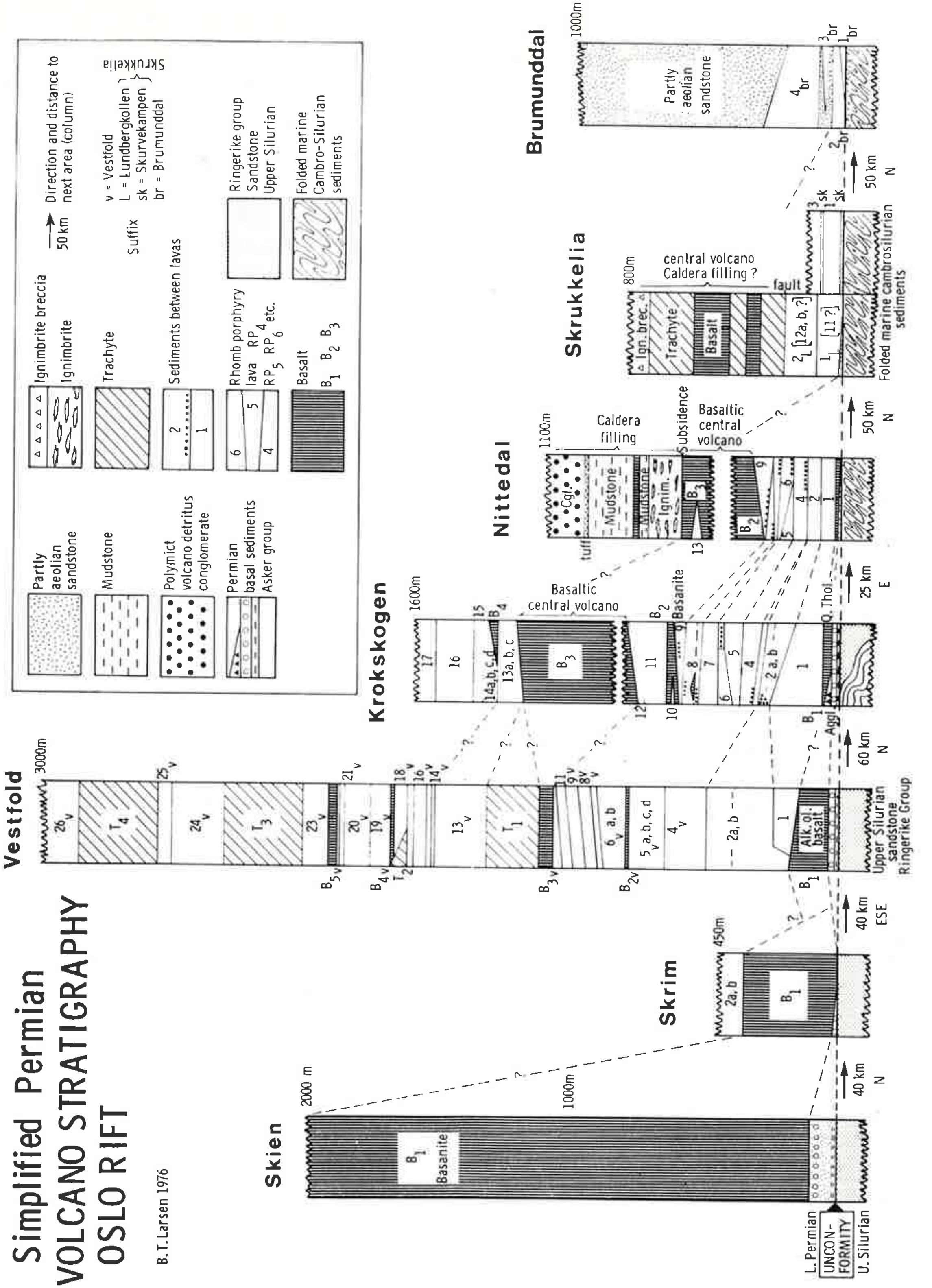
Fig. 3. Tilley–Muir normative mineral diagram of different basalts of the Oslo Region.

Oslo Graben started with basaltic eruptions, except in the northern areas (Rosendahl 1929, Ramberg & Larsen, in prep.). These basal basalts, which are thickest in the south and progressively thinner towards the north (Fig. 4), are everywhere given the designation B_1. Chemically the B_1 basalts change in compositions from south to north (Weigand 1975). The thick *Skien* basalt series in the south consists of undersaturated alkali olivine basalts, basanites (or basanitoids) of nephelinites with approximately 8% normative Ne. Nepheline is present (Segalstad 1976) (Table 2 and Fig. 3). The *Jeløya* B_1 basalts are alkaline and commonly of marginal type. Their proximity to the marginal fault zone and fissure zones seem to have favoured accumulation of locally thick piles of volcanics and pyroclastic rocks. The *Holmestrand* B_1 basalt series in Vestfold, is about 130 m thick or more (Brøgger 1933) and is made up of about 10–15 flows of mildly undersaturated alkali olivine basalt with normative Ne about 2.5%. Further north, at *Krokskogen*, the B_1 basalt largely consists of one single aphyric flow about 30 m thick. This B_1 basalt is oversaturated and quartz tholeiitic in composition (norm $Q > 5\%$). The complexity and chemical variety of B_1 basalts exclude the possibility that they are strictly comagmatic.

Geological evidence implies that the southern Skien basalts are the oldest and the northern Krokskogen tholeiites the youngest of the B_1 basalts, but all were erupted before the appearance of the first rhomb porphyry flow (RP_1). The Krokskogen B_1 basalt has a Sr^{87}/Sr^{86} ratio of about 0.7050. (Sundvoll, pers. comm. 1976) and, therefore, a direct genetic relationship to the rhomb porphyries (with ratio of 0.7040) seems unlikely.

The stratigraphically higher basalts (formerly numbered B_2–B_5, see Larsen, this volum), which erupted mainly from central-vent volcanoes, are partly

Fig. 4. Schematic stratigraphic synthesis of the Permian lavas in the major volcanic areas of the Oslo Region, from south to north.
Data from Oftedahl 1967, pers. comm. 1976, Rohr-Torp 1973, Sæther 1946, 1962, Ramberg 1976, Segalstad 1976, Naterstad 1971 and unpublished data from the authors.


Simplified Permian VOLCANO STRATIGRAPHY OSLO RIFT

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olivine tholeiites and mainly alkali olivine basalts. B_2 at Krokskogen is basanitic in composition whereas the Nittedal B_2-type is an alkali olivine basalt, clearly indicating a different source. The B_3 basalts are mostly olivine tholeiites or transitional types between alkali basalts and tholeiite. However, very few analyses are available for these central volcano basalts. The B_3 basalts are typically found as members in a complex (commonly termed the B_3 complex, Oftedahl 1960) which, in addition to the basalts, includes members of trachytic to rhyolitic composition, rhomb porphyry detritus and felsic layers (ignimbrites). Higher basalt flows are considered local with limited extension and varying stratigraphical position.

The Øyangen cauldron (Larsen, in prep.), which is the northernmost and youngest of four cauldrons linked together along a NNW trending line, is a typical illustration of the development of a basaltic central-vent volcano and subsequent cauldron subsidence. The basalts are alkali olivine basalts (and tholeiites) and constitute a differentiation series ranging from ankaramites to hawaiites, where the ankaramites are generally the oldest flows. Pyroclastic hawaiites dominate the uppermost part of the central volcano basalt sequence. Basalts containing xenocrysts of kaersutite amphibole are found in some cauldrons. The Øyangen cauldron contains basalts of this type in small necks defining a N-S trending direction.

The varying chemical compositions of the basalts are matched by similar variations within the generally gabbroic 'Oslo-essexitic' volcanic necks, which may represent feeders for some of the basalt flows. The 'double neck' at Vestby in the Precambrian just east of the Oslofjord fault zone consists of a large semi-circular intrusion (diameter about 0.8 km) of quartz tholeiite composition accompanied by a slightly smaller elliptical alkali olivine basaltic intrusion (Ramberg 1970). Both intrusions represent subvolcanic storage chambers (with low-pressure mineralogy, cumulus texture and igneous layering) separated by a screen of Precambrian gneisses that at one place is only 30 m wide.

Thus, in summary we have seen that there appear to be various volcanic 'provinces' within the graben area. These provinces are composed of different combinations of the major lava types and can be related to various geological environments with respect to the graben. There is a distinct decrease in thickness of the B_1 basalts from south to north (Fig. 4) and a distinct change in composition. An overall decrease in thickness from south to north is also recognized in the Permian sedimentary sequence (the Asker Group) below the volcanics (Henningsmoen, this volume). In the northernmost parts (Skrukkelia, Brumunddalen) the lavas extruded directly on top of eroded Cambro-Silurian rocks (Fig. 4). The extensive B_1 basalts in the south apparently extruded on a rather gentle peneplain before the onset of major faulting. However, towards the north, for instance in the Skrukkeli area, we find local higher basalts and felsitic lavas deposited at stratigraphic positions above RP_{11}–RP_{12} (of Krokskogen type). Field evidence indicates extrusion upon a broken-up surface caused by concomitant faulting at the time of extrusion.

A general younging towards north is also recognized in the cone-in-cone cauldron complexes where the most recent cauldron is commonly found to the north (Larsen, this volume).

The volcanics carry with them information about the early stages of the evolution of the Oslo Graben. Studies of the plutonic rocks are essential for interpreting the subsequent stages necessary for a complete tectonomagmatic model of the rift. The *plutonic* rocks of the Oslo Region, and their petrology, are reviewed in a separate paper (Neumann, this volume) and the deepseated foundering based on geophysical interpretation is summarized by Husebye and Ramberg (this volume). It only needs to be emphasized that recent geophysical studies (Ramberg 1976) reveal that the felsic rocks which predominate in the surface exposures are exceeded by dense rocks at depth by a ratio of about 10 to 1. Thus, volumetrically there is no longer any objection to the idea that the felsic rocks originated from a mantle-derived basaltic parental magma. The deep-seated dense mass is located right below the felsic batholiths and follows closely the axis of the graben. It also follows a zone of crustal attenuation. The deep-seated dense rocks are tentatively interpreted as a paleorift cushion formed by fractional melting in the upper part of a mantle diapir. This model fits with geochemical data (Heier & Compston 1969, Raade 1973) suggesting that the felsic igneous rock suite was derived from lower crustal or, preferably, upper mantle depths. The intermediate to felsic rocks rose towards the surface, aided by plastic deformation at depth, crustal break-up and separation combined with magmatic stoping at higher crustal levels.

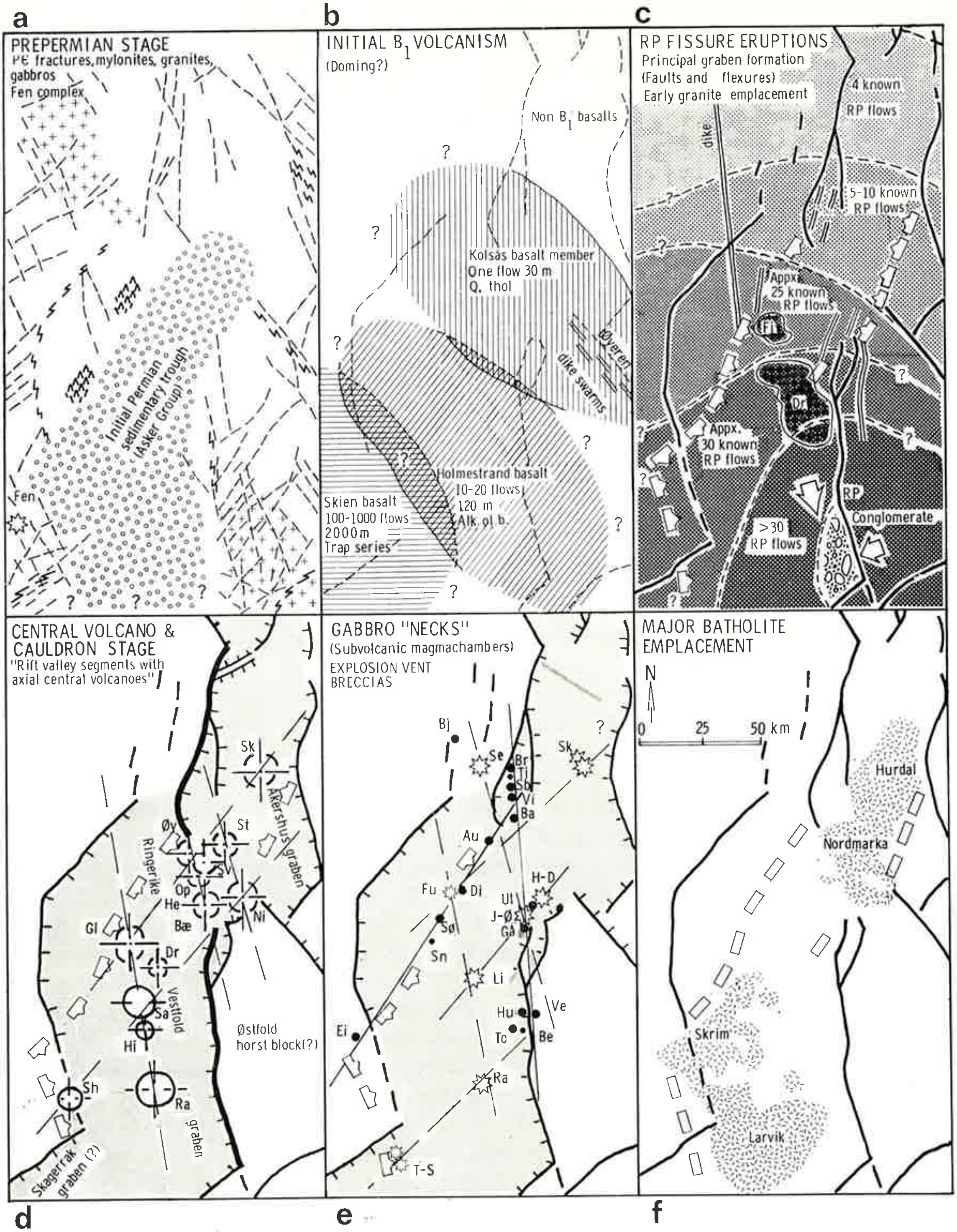
Tectonomagmatic evolution

Fitting together the various sets of data leads to the tentative model sketched in Figs. 5 & 6.

Stage 1 (Fig. 5a). A general pre-rift stage of repeated deformational and intrusive events imprinted a marked fracture pattern, predominantly composed of 'diagonal' (NW-SE and NE-SW) trends, upon the brittle upper crust (Fig. 1a). Approximately the same directions are defined by a number of frictional breccias and crush belts.

A line through the Eocambrian/Early Cambrian Fen alkaline complex and a couple of elongate major Precambrian gabbroic intrusions served as an active tectonic zone and coincides with the incipient western border of the Oslo Region. The occurrence of several NNE-trending sedimentary troughs that developed in Cambrian to Silurian times in the area of the present Oslo Region is not indicated on the figure. The Late Carboniferous/Early Permian shallow sedimentary trough is, however, indicated (Fig. 5a).

At the onset of Permo-Carboniferous rifting, the near coincidence between the older tectonic lines and many of the graben features (fault lines, dikes, alignment of volcanoes, etc.) reflects the response of the structurally anisotropic continental crust to tensional stress. While the overall position and regional


a
PREPERMIAN STAGE
PЄ fractures, mylonites, granites, gabbros
Fen complex
Initial Permian sedimentary trough (Asker Group)
Fen
?
b
INITIAL B1 VOLCANISM
(Doming?)
Non B1 basalts
Kolsås basalt member
One flow 30 m
Q. thol
Øyeren
dike swarms
Holmestrand basalt
10-20 flows
120 m
Alk. ol b.
Skien basalt
100-1000 flows
2000 m
Trap series
?
c
RP FISSURE ERUPTIONS
Principal graben formation
(Faults and flexures)
Early granite emplacement
4 known RP flows
5-10 known RP flows
dike
Appx. 25 known RP flows
Fi
Dr
Appx. 30 known RP flows
>30 RP flows
RP
Conglomerate
?
d
CENTRAL VOLCANO & CAULDRON STAGE
"Rift valley segments with axial central volcanoes"
Sk
Akershus graben
Øy
St
Ringerike
Op
He
Bæ
Ni
Gl
Dr
Sa
Vestfold
Hi
Østfold horst block(?)
Sh
Ra
graben
Skagerrak graben (?)
e
GABBRO "NECKS"
(Subvolcanic magmachambers)
EXPLOSION VENT BRECCIAS
Bj
Se
Br
Ti
Sb
Vi
Ba
Sk
?
Au
Fu
Di
H-D
Ul
J-Ø
Gå
Sø
Sn
Li
Hu
Ve
To
Be
Ei
Ra
T-S
f
MAJOR BATHOLITE EMPLACEMENT
N
0 25 50 km
Hurdal
Nordmarka
Skrim
Larvik

trend of the rift certainly reflect the geometry of the deep-seated diapiric movements, the near-surface fracturing was evidently controlled to some extent by pre-existing lines of weakness.

Stage 2 (Fig. 5b). The initial B_I basalt volcanism startet in the Skien area with the eruption of several hundred individual flows forming a huge stratoid trap series of undersaturated basalts. The series' structure (without known breaks or unconformities), composition and position relative to the graben are similar to the stratoid fissure basalt series occurring outside of the main Ethiopian rift and Afar (e.g. Mohr 1971, C.N.R. – C.N.R.S. Afar Team 1973, Pilger & Røsler 1976). Since domal uplift is commonly genetically connected with the initial stages of rifting (though clear evidence from the Oslo paleorift is lacking), the Skien basalts may have been deposited in an interdome basin.

The systematic change in the number of flows, aggregate thickness and composition of the B_I basalts towards the east and especially the north (Fig. 5b), indicates a younging of the B_I phase towards the north and a migration of the volcanism towards central parts of the rift. These flows represent possible fissure and/or multicentre eruptions from relatively shallower and more depleted mantle sources. Further north (Skrukkelia, Brumunddalen), the B_I basalts are missing.

Stage 3. Fig. 5c summarizes the rhomb porphyry fissure eruption stage which occurred during normal faulting and 'rift valley' formation. Major RP-dikes follow the characteristic NNW (or N) trend of the graben (see Fig. 1b). The rhomb porphyry eruptions may have begun at about the same time all over the area, or eruptions may have begun slightly earlier in the south (more frequent RP flows in Vestfold) than in the north (Figs. 4 & 5).

The major Oslofjord fault developed at this stage, the largest vertical displacements (about 3 km) occurring to the south. The formation of the fault scarp caused the accumulation of rhomb porphyry (and other lava) debris in the low areas inside the graben. These deposits are found as RP-conglomerates (fanglomerates) on the Oslofjord islands, indicating sediment transportation chiefly from the east and north.

Fig. 5. Schematic cartoon showing the igneous and tectonic evolution of the Oslo Graben (see text).
Abbreviations:
Biotite granites: Fi - Finnemarka, Dr - Drammen.
Cauldrons: Sk - Skrukkelia. St - Stryken, Ni - Nittedal, Øy - Øyangen, Sv - Svarten, He - Heggelia, Op - Oppkuven, Bæ - Bærum, Gl - Glitrevann, Dr - Drammen, Sa - Sande, Hi - Hillestad, Ra - Ramnes, Sh - Skrehelle.
Gabbro necks (black dots): Br - Brandbukampen, Ti - Tingelstad, Sb - Sølsberget, Vi - Viksbergene, Ba - Ballangrudhøgda, Ul - Ullernåsen, Gå - Gåsøya, Au - Aurenhøgda, Di - Dignes, Sø - Sønstebyflakene, Sn - Snaukollen, Ei - Eiangen, Hu - Husebykollen, Ve - Vestby, To – Tofteholmen (and Randvikholmen), Be – Bevøy, Bj – Bjonvika.
Explosion vent breccias (open stars): Sk - Skrukkelia, Se - Sevaldrud, H-D - Holmen - Dagali, J-Ø - Jar - Øraker, Fu - Furetangen, Li - Lindum, Ra - Ramnes, T-S - Tveitan - Stokkevannet.

From the central part of the region, Gaut (1975) has demonstrated that the major biotite granite in the Drammen district predates some of the volcanic structures (e.g. ring dike) of the Drammen cauldron. This timing indicates that the emplacement of the Drammen (and possibly the neighbouring Finnemarka) granite took place at an early phase of the development of the Oslo Graben, a view that has been substantiated by recent radiometric dating of 284 ± 13 m.y. for the granite (Sundvoll, this volume). The granite region separates the Krokskogen and Vestfold volcanic areas, and may represent an early uplifted area. Granites predating parts of the trap basalts are known from other rift regions, such as the Afar region (C.N.R.–C.N.R.S. Afar Team 1973).

Stage 4. Figs. 5d & e summarize the central volcano and cauldron stage. The principal rift (graben) had formed and a complex 'rift-valley' runs from Skagerrak to Mjøsa (Plate 2). The generally NNE-trending graben is composed of two north-trending graben segments, the *Vestfold–Ringerike graben* (in the SW part) and the *Akershus graben* (to the NE) (Fig. 5d). The northeastern segment is positioned in an *en échelon* manner relative to the southwestern segment. The two segments are nearly separated by a northward wedging block (the Østfold horst). Both graben segments are asymmetrically tilted towards the central N-S trending Oslofjord fault and its northward extrapolation (Randsfjord–Hundselv fault). The two faults form together the characteristics of a scissor fault. This kind of regular geometrical arrangement is also known from rift segments along the Mid-Atlantic Ridge (Ramberg & van Andel 1977). The N-S Oslofjord/Randsfjord-Hundselv line is followed up by a complex dike swarm both in the Bærum/Oslo/Nesodden area and in the Hadeland area. Another dike swarm is apparent along the eastern boundary of the Østfold horst (Plate 2).

Both the Vestfold–Ringerike and the Akershus graben segments display maximum subsidence in their southern parts. These are also the areas where major composite batholiths (see Fig. 5f) were emplaced at a subsequent stage.

The transition from the stage (3) of fissure eruptions to the central volcano stage (4) is well documented in the field by rhomb porphyry flows interfingering with basaltic and felsic flows (e.g. Ramnes cauldron (Oftedahl 1967) in the Øyangen cauldron (Larsen in prep) and in the Skrukkelia area in the north (Ramberg & Larsen in prep.)). This transition indicates a reduction of tensional stress. Most of the central volcanoes were built as basaltic lava cones; only those in the south (Ramnes & Hillestad) may have been of bimodal type (basalt-felsic volcanics) or been built as trachytic central volcanoes (Oftedahl and Petersen, this volume).

The central volcanoes are found in two (or three) principal positions relative to the graben outline. (Note that the Kongsberg block in Fig. 5d is our interpretation. We believe that this block of Precambrian rocks represents an intermediate stepping stone between the central graben and the relatively uplifted shoulder). The positions of the central volcanoes are as follows:

I. A string of central volcanoes/cauldrons extends along the *axial line* of the Vestfold–Ringerike graben (from Ramnes in the south to Glitrevann in the north). This line continues into a 130 km-long RP dike (Fig. 5c). The *Skrukkelia* cauldron (only remnants) further to the north is situated on the central axis of the Akershus graben.

II. Six central volcanoes/cauldrons (or cauldron remnants) occur where the southern graben segment is offset from the northern one in the Oslo district. This cluster of cauldrons is situated close to the apex of the wedge-shaped Østfold horst block. The group forms a square, the four corners of which are the Nittedal, Bærum, Øyangen and Stryken cauldron complexes. The Stryken cauldron may possibly represent a more deep-seated ring complex.

III. The Skrehelle (remnant) cauldron (Segalstad 1975), which is part of the Skrehelle–Sande–Drammen–Bærum 'string', occurs at the southwestern margin of the Vestfold–Ringerike graben. This 'string' parallels the Glitrevann–Øyangen–Skrukkelia 'string'.

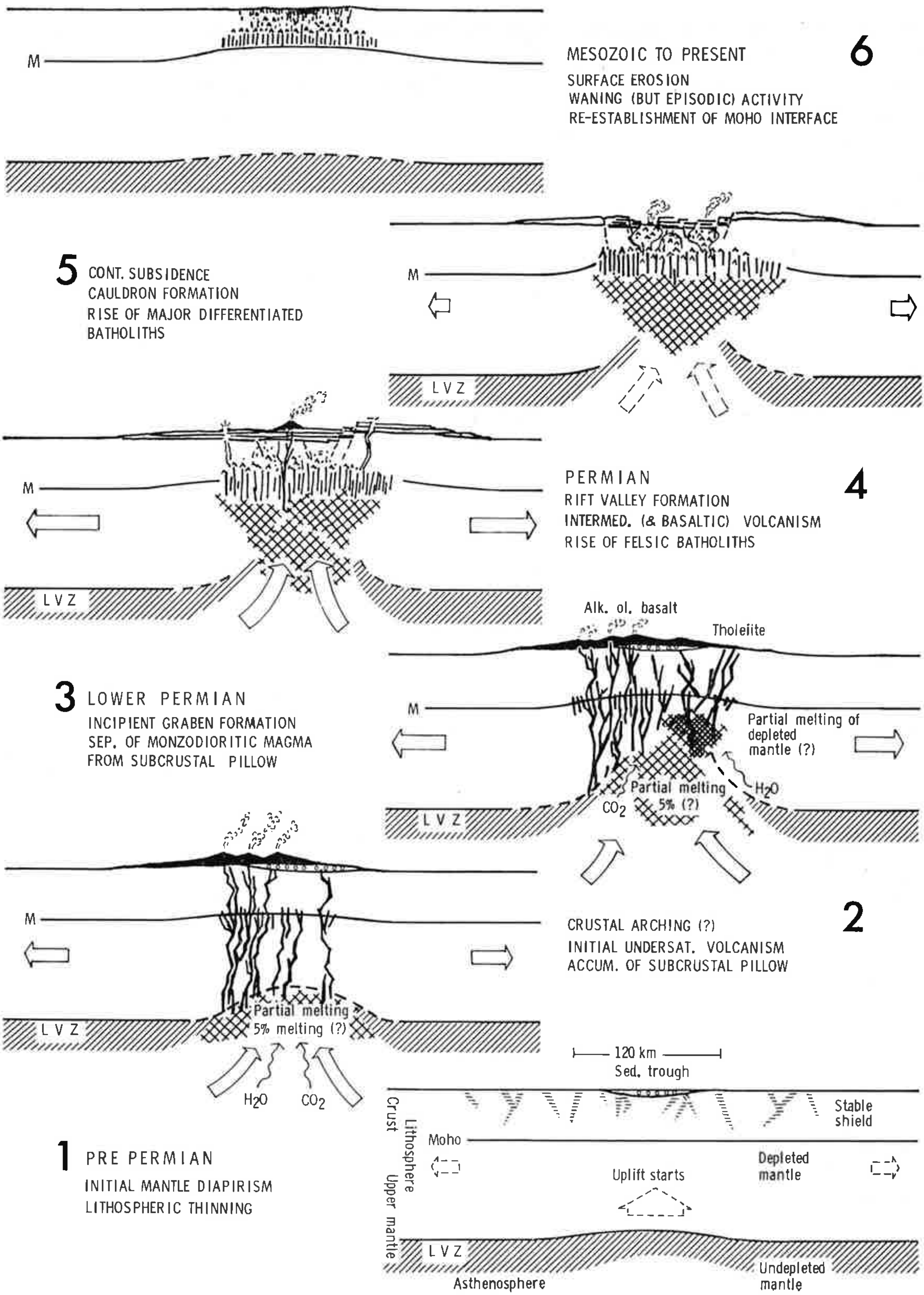
The alignment of the central volcano/cauldron complexes defines a strikingly regular pattern which is parallel to major and minor faults of the graben (Fig. 5d). The volcanoes are often located at the cross-points of this grid pattern. There also appears to be a somewhat regular spacing of the volcanoes. The average spacing (19 measurements) is close to 28 km (st.dev. ± 10 km). This value, which is somewhat larger than the found in the Afar region but less than in the Kenya rift (Mohr & Wood 1976), indicates a crustal thickness at the time of intrusion (Vogt 1975) of about 23 km for the Oslo Graben. This thickness agrees well with geophysical interpretations (Ramberg 1976) which suggest that the top of the paleorift 'cushion' is found at a depth of about 20 km. The formation of central volcanoes throughout time may have progressed from south to north. This may be exemplified by the group of cauldrons north of the city of Oslo, which all developed from basaltic central volcanoes to calderas. If one can apply the rhomb porphyry stratigraphy of the areas as a relative time marker, there is some evidence that Nittedal is the oldest complex of this area, and that the major basaltic eruptions took place at B_2 time (RP_9). In Bærum, further to the west, we find that the similar event occurred at B_3 time (or RP_{11}) whereas Øyangen, furthest to the north, is the youngest of them all (around RP_{15}–RP_{17}). The interdigitated Svarten segment experienced the event at RP_{14}–RP_{15} time (see Larsen, this volume).

Fig. 5e, which illustrates the distribution of the gabbroic to syenodioritic subvolcanic necks ('Oslo-essexites') and volcanic vent breccias, probably does not represent a specific stage of its own in the evolution of the rift (graben). The gabbroic necks clearly predate the emplacement of the major felsic batholiths, but otherwise there is no precise absolute or relative dating of these intrusions. They might have formed at different times but, contrary to the common view, we suggest that the bulk of the necks formed during the central volcano stage, an interpretation previously suggested by Dons (1952). Similar arguments are presented for some of the volcanic vent breccias (Dons 1952). As can be seen from Fig. 5e, the volcanic vents are generally spatially associated with cauldron/central volcanoes, and hence probably represent a late, violent phase in the central volcano stage. Both the gabbroic necks and the explosion breccias lie on the same lineaments as the master faults and the strings of cauldron subsidences. One of these lineaments coincides with the border between the Kongsberg block and the main Vestfold–Ringerike graben segment. This border, which is one of several monoclinal flexures, developed during the stages 3 to 4. It now marks the western boundary of the Oslo Region proper (Plate 2).

Stage 5 (Fig. 5f). The emplacement of the major composite batholiths in the two graben segments represents the last of the main stages in this tentative scheme. It certainly was already in progress during stages 3 and 4 and this emplacement gradually obliterated several of the earlier formed features. Remnants of earlier monzonitic intrusives as well as possible cauldron fragments occur at many places within the largely syenitic northern batholith (the Nordmarka–Hurdalen batholith). The southern Larvik–Skrim batholith of largely monzonitic composition cuts the hypothetic boundary fault and invades far into the Precambrian shoulder. Before their final emplacement and crystallization the batholithic magmas were the source for some of the intermediate to felsic volcanics. The two composite batholiths are completely separated from the intervening old granite complex by Cambro–Silurian rocks and underlying Precambrian gneisses that subsided with the graben blocks. Although the various plutonic rocks of the batholiths are cut by a number of minor faults and joints, major faults are lacking except in the old granitic complex indicating that the *majority* of the plutonic rocks intruded towards the end of a long period of tensional faulting and igneous activity.

The near-surface effects summarized above are all considered responses to first-order mantle processes. Fig. 6 presents an evolutionary sequence by means of generalized cross-sections. This sequence is based on analogy with other (but modern) continental rifts as well as on geophysical evidence of a thinned crust and an anomalous paleorift 'cushion' below the Oslo Rift (Ramberg 1976). The rise of a hot asthenospheric diapir resulted in partial melting in the top portion of the diapir and the discharge of basaltic material into the base of the gradually thinned overlying crust. This led, in turn, to the formation of the Permo-Carboniferous Oslo Rift with its variety of alkaline igneous rocks. The model explains compositional differences between the early formed undersaturated basalts, derived from great depth, and the subsequent saturated central rift basalts, derived from relatively shallower depths. The deep

Fig. 6. Evolutionary stages of the Oslo Graben illustrated by a series of cross-sections. Graben formation and volcanism are viewed as secondary effects of mantle diapirism, crustal thinning and injection of mantle-derived basic material. (See text).


M
MESOZOIC TO PRESENT
6
SURFACE EROSION
WANING (BUT EPISODIC) ACTIVITY
RE-ESTABLISHMENT OF MOHO INTERFACE
5
CONT. SUBSIDENCE
CAULDRON FORMATION
RISE OF MAJOR DIFFERENTIATED BATHOLITHS
M
LVZ
M
LVZ
PERMIAN
4
RIFT VALLEY FORMATION
INTERMED. (& BASALTIC) VOLCANISM
RISE OF FELSIC BATHOLITHS
Alk. ol. basalt
Tholeiite
3
LOWER PERMIAN
INCIPIENT GRABEN FORMATION
SEP. OF MONZODIORITIC MAGMA FROM SUBCRUSTAL PILLOW
M
Partial melting of depleted mantle (?)
Partial melting
5% (?)
CO$_2$
H$_2$O
LVZ
M
LVZ
Partial melting
5% melting (?)
H$_2$O
CO$_2$
CRUSTAL ARCHING (?)
2
INITIAL UNDERSAT. VOLCANISM
ACCUM. OF SUBCRUSTAL PILLOW
120 km
Sed. trough
Stable shield
Crust
Lithosphere
Upper mantle
Moho
Depleted mantle
Uplift starts
LVZ
Asthenosphere
Undepleted mantle
1
PRE PERMIAN
INITIAL MANTLE DIAPIRISM
LITHOSPHERIC THINNING

gabbroic source produced magma of intermediate composition which rose to higher crustal levels. Continued magmatic differentiation led to the intermediate to felsic rocks that intruded the fractured upper sialic crust. A review of petrogenetic hypotheses for the plutonic rocks is given by Neumann (this volume).

Aftermath

Evidence for volcanotectonic activity within the Oslo Graben proper after Permo-Carboniferous time is rather scarce. Radiometric ages from diabase dikes (Dons 1977, Larsen 1975) indicate emplacement during the Upper Permian and even the Triassic (219 ± 6 m.y.). A Triassic age has also been tentatively suggested for the loosely consolidated, partly aeolian sandstone on top of the Brumunddalen rhomb porphyry lava flows (Spjeldnæs 1972). A late Mesozoic age has been suggested for continued subsidence and rotational block-faulting along the Oslofjord boundary fault (Størmer 1935). This zone seems still to represent the general locus of some of the largest earthquakes known in Fennoscandia. On the whole, the present seismic activity in the Oslo Region is relatively modest, but higher than that of the surrounding Precambrian terrain (Husebye & Ramberg, this volume).

The southwestward continuation of the Oslo Graben below the Skagerrak Sea (the Bamble trough) has been inferred from geophysical studies (gravity in particular) as well as from scattered geological evidence along the Norwegian Skagerrak coast (e.g. Ramberg 1976). The Precambrian coastal area contains rhomb porphyry and diabase dikes of predominantly Permian but also of possible Tertiary age (Storetvedt 1968). On the basis of aeromagnetic data, a Tertiary age has also been suggested for the composite volcanic plug outside Kristiansand and for another offshore volcanic feature, i.e. the possible dike-like feeder outside Risør further to the NE (Åm 1973). Post-Jurassic basalt has been dredged from the north central part of the Skagerrak (Noe-Nygaard 1967). The occurrence of Lower Eocene volcanic ash layers in Denmark (Pedersen et al. 1975, Norin 1940) imply the presence of Tertiary basalt volcanoes somewhere in the southern parts of the Skagerrak Sea. Thus, within the Skagerrak part of the Oslo Rift, there is evidence of a post-Permian period of igneous activity at about Late Mesozoic to Paleocene age.

Concluding remarks

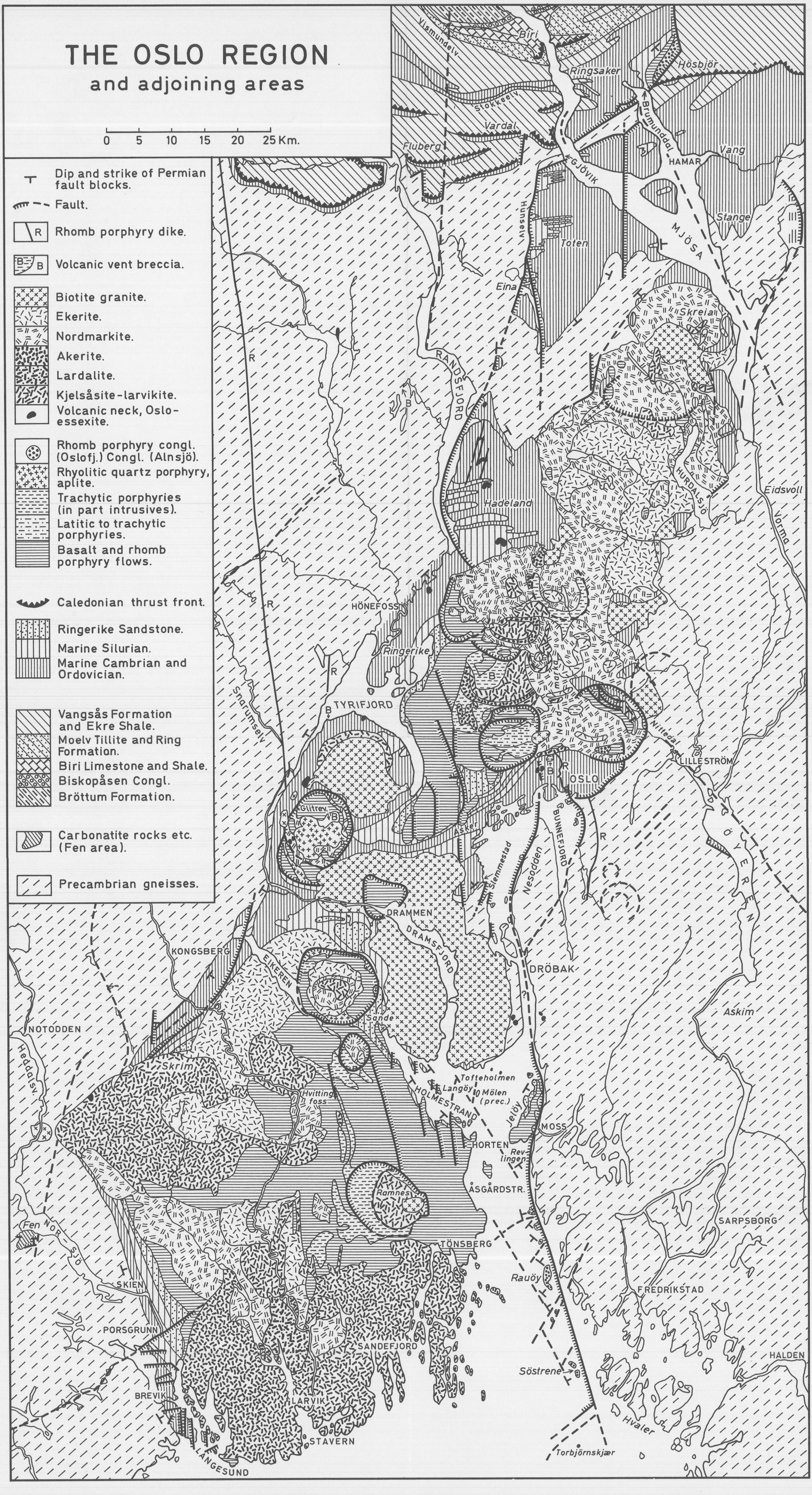
In a regional context, the Oslo Graben (and Rift) is an integral part of a larger system of taphrogenic tectonic elements beginning to form in the Permo-Triassic intracratonic stage (P. A. Ziegler 1975) of northwest Europe. The Earth's crust under most of the North Sea and adjacent land areas seems to consist of a mosaic of cratonic fragments. The Oslo Graben (and more widely the Oslo Rift zone) is located at an intersection of the two dominant fracture directions. The two major directions trend about NE–SW (the 'Caledonian' direction) and about NW–SE (the 'Dinaric' or 'Tornquist' direction). The latter direction is exemplified by the Tornquist line which defines the Fennoscandian Border zone between the fragmented southwestern extension of the craton and the more cohesive part of the Fennoscandian Shield to the north and the east. Permian rhomb porphyry dikes and diabase dike-swarms follow these two directions and seem to radiate from the two intrusive centres within the Oslo Graben.

Thus, to the southwest, the Oslo Rift intersects with the NW-SE trending Danish-Polish Depression (see Husebye & Ramberg, this volume, fig 1), whereas further southwest it is continued by the Permian Horn Graben and the zigzagging Central Graben of the North Sea (Ramberg 1971, Burke & Dewey 1973, Whiteman et al. 1975, Ramberg & Smithson 1975, Kent 1975, W. H. Ziegler 1975, P. A. Ziegler 1975, 1977). The Permian alkaline igneous activity within this system represents a widespread event which appears to have initiated a prolonged period of repeated rifting and volcanism which lasted throughout the Mesozoic (e.g. Howitt et al. 1976, Færseth et al. 1976, Klingspor 1976, Lorenz & Nicholls 1976). The overall timing and similarity of the volcanic products suggest that the various tectonic and igneous pulses recorded within the rift system reflect large-scale tectonic phases. Hence, a preliminary hypothesis is that the Oslo Graben (and Rift) was formed in response to post-orogenic, Hercynian compression, leading to a predominant N-S trending shear system. The possible anticlockwise rotation of the cratonic fragments caused the embryonic crustal break-up and opening of the Oslo Graben and Skagerrak area. The Oslo Graben appears to represent the most active magmatic segment of the rift system in early Permian time, but the magmatic activity can be traced all the way from the Särna complex about 250 km north of Oslo to the Horn Graben west of Denmark.

Later on, crustal rupture systematically shifted to localized zones further to the west. The rather modest evidence of Mesozoic and Tertiary tectonic and igneous events within the Oslo Rift proper is held to reflect subsequent stages of rifting in the Central Graben of the North Sea and the early opening of the North Atlantic.

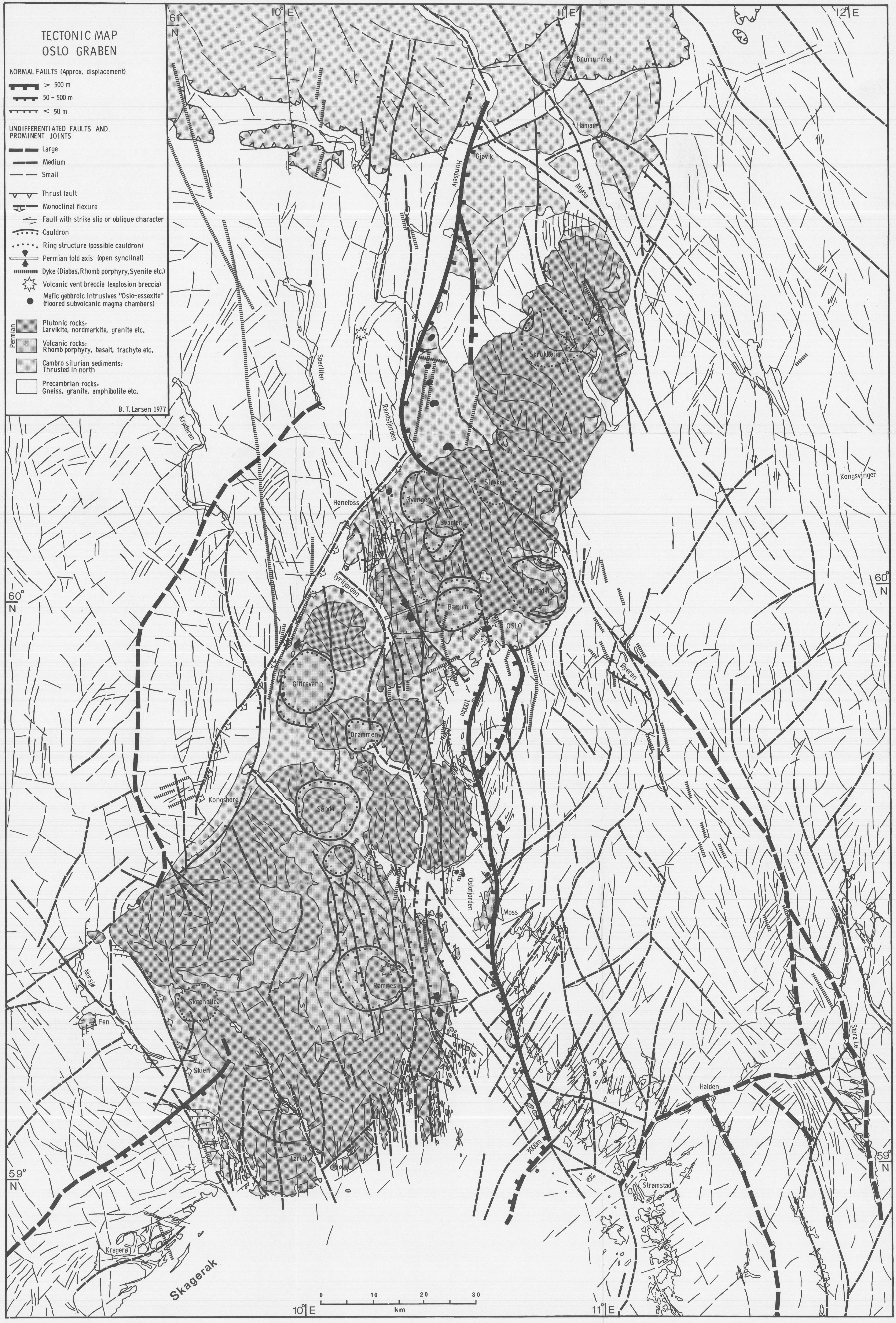
Ramberg & Larsen (after Ramberg 1976, revised after Oftedahl 1960)

NGU 337 – Dons & Larsen (Eds.) – Plate 1



THE OSLO REGION

and adjoining areas



TECTONIC MAP
OSLO GRABEN