GEOPHYSICAL EVIDENCE FOR A BURIED VOLCANIC MOUNT IN THE SKAGERRAK

P. VALLABH SHARMA

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This paper presents a qualitative interpretation of the available gravity and aeromagnetic data over the Skagerrak. The amplitude and shape pattern of both gravity and aeromagnetic anomalies suggest the possible location of a fairly extensive residual volcano buried at a depth of about 250 m below the marine sediments. The depth to the top of the basement estimated from the magnetic anomaly map is around 5000 m. An analysis of the prominent magnetic anomaly indicates the intensity of the natural remanent magnetization (NRM) to be predominant and its direction to be roughly opposite to that of the present geomagnetic field. The palaeomagnetic pole position inferred from the direction of NRM (presumably of thermo-remanence origin) is compared with that of known Tertiary poles of the volcanics of the neighbouring regions. Some implications of the geophysical findings with regard to the correlation of the Skagerrak volcano with the Eocene ash beds of Northern Denmark are discussed.

The geology of the area between Norway and Denmark (Skagerrak) is practically unknown, although some second-hand information is available on the basis of conjectured extensions of borehole records (Sorgenfrei & Buch, 1964) and the presence of erratic boulders in northern Jutland (Skeat & Madsen, 1898). Fig. 1 shows the bathymetrical map (Holtedahl, 1962) of the submarine area together with some geological data along the coastal zones.

Of the many interesting problems in this area are those concerning the character and thickness of sedimentary deposits and the nature of the rock masses below them. The possibility of occurence of volcanics in the northwest part of the Skagerrak has been earlier suggested in an attempt to establish some sort of correlationship with the Eocene ashes of north Jutland (Bøggild, 1918; Andersen, 1937; Norin, 1940) and with the Egersund dolerites (Storevedt, 1966). In addition, recently dredged basalt material from the southern flank of the Norwegian Deep has led Noe-Nygaard (1967) to postulate the probable occurence of sills or dykes in this part of the area.

In the last few years, under the scheme of 'Skagerrak Project' some geophysical investigations have been conducted to study the geologic structure of Skagerrak, but so far the data of only a few of these investigations have been published and that too without any geological interpretation of the results.

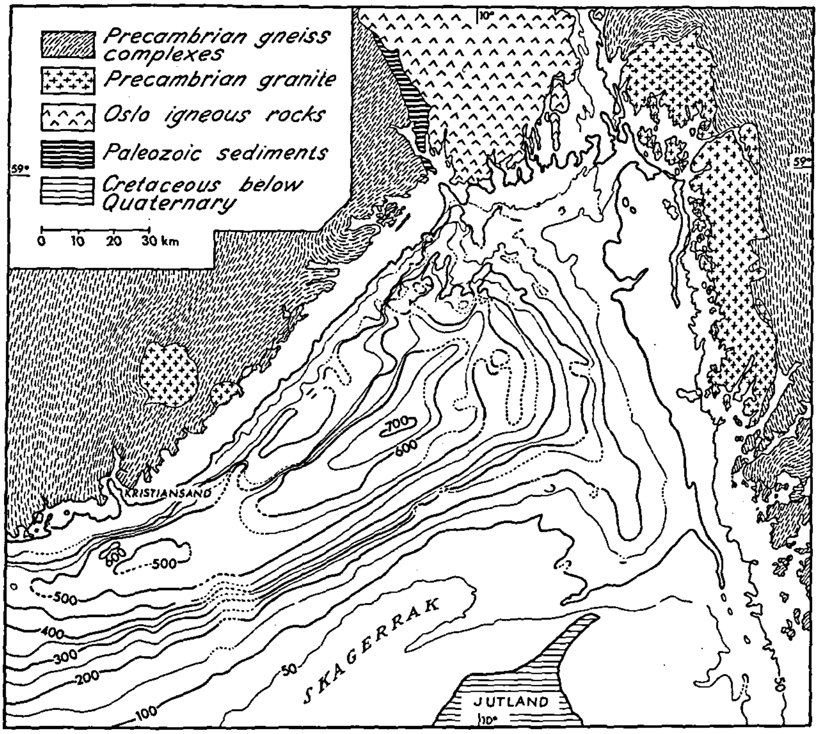

Fig. 1. Bathymetric map of Skagerrak after Holtedahl (1962).

This paper presents a qualitative interpretation of the available seaborne gravity (Andersen, 1966) and airborne magnetic data (U.S. Naval Oceanographic Survey, 1965) in terms of the causative structural features. A discussion is also made of the palaeomagnetic and geological implications of the geophysical findings.

Correlation of gravity and magnetic data

Fig. 2 shows the Bouguer anomaly map of the area. In fig. 3 is shown the total magnetic intensity chart. In spite of the relatively scanty data available around the gravity high, a correlation with the fairly extensive magnetic low could be attempted. The simultaneous occurence of gravity and magnetic anomalies at approximately the same location in north-west part of the Skagerrak indicates that a single causative body is possibly the source of both anomalies, and the body is showing a marked contrast both in density and magnetization with respect to the surrounding rocks. Further, the relative extent and amplitude of the prominent negative

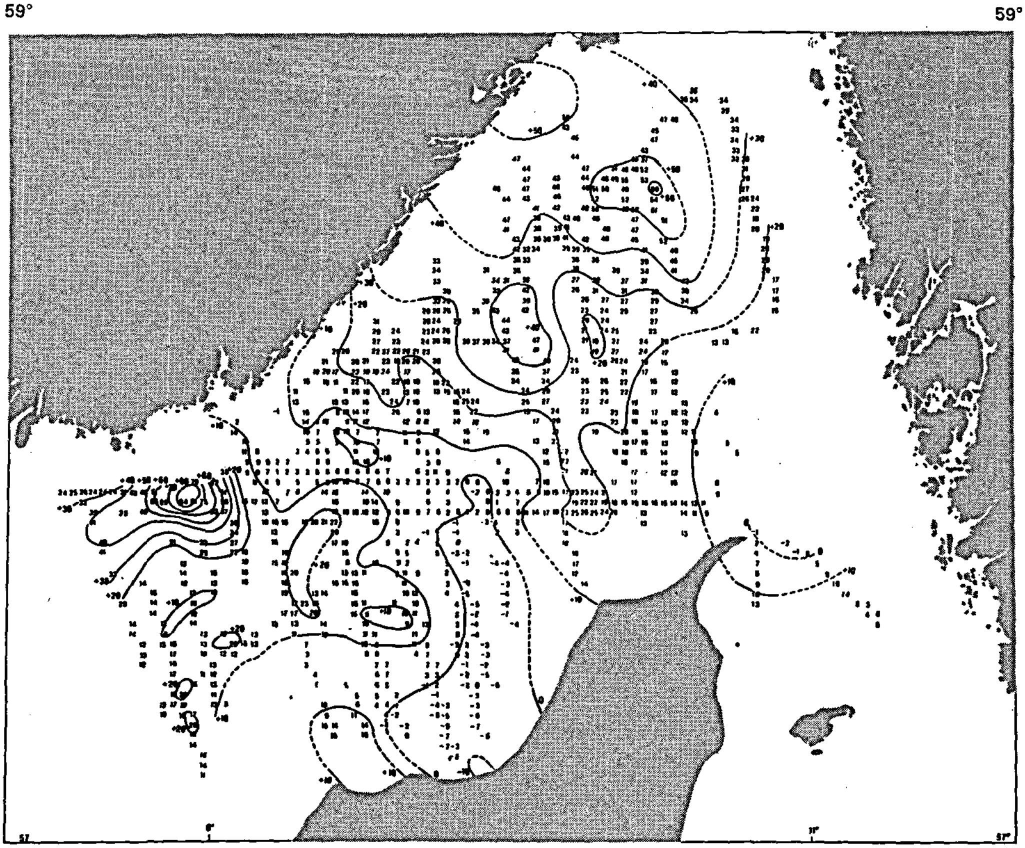

Fig. 2. Bouguer Anomaly map of Skagerrak after Andersen (1966).

magnetic anomaly suggests the strong predominance of remanent magnetization which is a usual characteristic of volcanic bodies acquiring a permanent magnetism during their cooling below the Curie point temperatures.

Direction of magnetization in the anomalous body

The general pattern and shape of a magnetic anomaly picture depend very much on the direction of the total magnetization vector J which is a vectorial sum of the induced magnetization J_i and the remanent magnetization J_r. An estimate of the direction of the magnetization vector J is, therefore, of utmost importance in the interpretation of magnetic anomaly maps, and for this purpose two different techniques are employed. The one most widely used involves an actual measurement on oriented samples of the rock body, but it can not be applied to deeply buried bodies. For

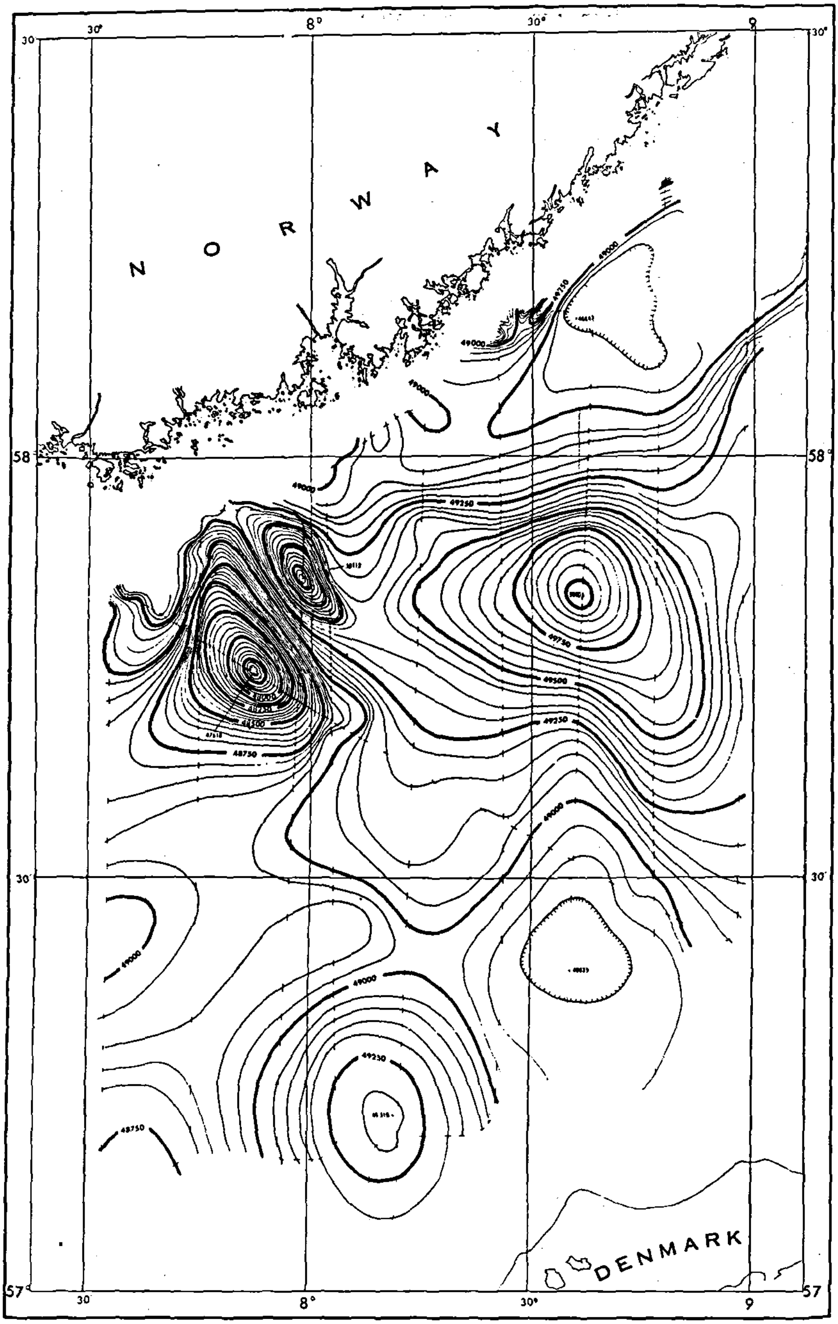

Fig. 3. Skagerrak. Total Magnetic Intensity Chart. Reproduced by permission of the U. S. Naval Oceanographic Office.

submarine bodies like sea-mounts whose geometry is reasonably well defined by detailed bathymetric maps, several methods exist (*e.g.* Vacquier, 1962; Sharma, 1966) which enable determination of the total magnetization vector. However, if the geometrical parameters of the body are unknown as is the case for buried features, the problem becomes rather complicated. Recently a new method has been suggested by Zietz & Andreasen (1967) which though originally developed for prismatic blocks, could be extended to bodies of other shape. In this method, the inclination I of the magnetization vector is estimated by the ratio of the amplitude of the positive to the negative anomaly, and the azimuth A from the angle between the magnetic north and the line joining the locations of the maximum and minimum of the regionally corrected anomaly. On applying this method to the Skagerrak aeromagnetic anomaly (see fig. 3) we roughly get I to be - 60° and A to be 210° for the direction of the magnetization vector. The fact that this direction is strikingly different and roughly opposite in sense to that of the present geomagnetic field, goes to show that the contribution of induced magnetization in the case is very little and the remanent magnetization intensity is strongly predominant. A discussion as to the palaeomagnetic significance of the remanent magnetazation of the Skagerrak anomalous feature shall be made at a later stage.

Estimate of the depth to the top of the body

The next step in the interpretation is the estimation of the depth to the top of the anomalous body. Vacquier's method (1951) for depth determination has been most widely applied to cases where the anomalies are caused by basement features with magnetic polarization in the direction of the present Earth's field, and as such it can not be applied to the prominent negative anomaly under investigation. However, a weak positive anomaly on the right side of fig. 3 shows a pattern characteristic of magnetic polarization colinear with the direction of the Earth's field. An analysis of this anomaly by Vacquier's method yields depth to the top of the basement around 5200 m. Taking into account the flight altitude of 300 m and the submarine depth of about 500 m (from fig. 1), it gives an estimate of the thickness of overlying sedimentary cover to about 4400 m. This appears to be reasonable in view of the conjectured estimate of an extrapolated figure of around 4500 m from borehole records (Sorgenfrei & Buch, 1964), and a figure of about 4200 m arrived on the basis of seismic refraction and reflection shooting (Hirschleber *et al.*, 1966; Aric, 1968).

Reverting to the prominent anomaly on left of fig. 3, the depth to the top of the causative volcanic body could be roughly estimated by assuming the magnetization to be caused by an equivalent magnetic doublet. For a full account of the magnetic doublet theory in the interpretation of aeromagnetic anomalies, the reader may refer to the original paper by Henderson & Zietz (1967). An analysis of the steep anomaly gradients by this method yields d (depth to the top of the volcano) to be about 1150 m and

l (the vertical extent of the body) to be nearly equal to 3.5. d. Taking into account the flight altitude of 300 m and a submarine depth of about 600 m, it indicates a sedimentary cover of only about 250 m overlying the vocanic mount. It must, however, be pointed out that in view of the relatively scanty data defining the magnetic anomaly (due to large line spacing of flights), the above estimated figures are at best of a semi-quantitative value. With the availability of more detailed gravity and magnetic survey data, a more reliable quantitative interpretation by model calculations can be attempted.

Magnetization of a residual volcano

Because of certain ferromagnetic properties of their constituent lavas, residual volcanos are actual markers of the geomagnetic field which existed at the time of their formation. For a better understanding of the significance of this ancient field direction, it is essential to know about the magnetization process (thermoremanence) involved.

Present-day magmas reach the earth's surface with temperatures of about 900°–1200°C, depending on their composition. The temperature of extruded olivine basalt (viscous fluid) from recent Surtsey eruptions has been found to be around 1100°C (Einarsson, 1966). As the temperature decreases, the viscosity increases and the fluidlike motion ceases around 800°C. By the time the most important Curie point, namely 578°C (of magnetite) is reached, a basaltic lava is already a solid. During further cooling below the Curie point, a lava placed in a steady magnetic field acquires a relatively stable thermo remanent magnetization (TRM) which is parallel to the direction of the ambient field. Measurements on recent igneous rocks, including lavas, show their NRM (essentially TRM) to be parallel to the direction of the axial geocentric dipole, thus the secular variation of the geomagnetic field is averaged out.

The direction of the remanent magnetization (in cases where the contribution of induced magnetization is negligible) as worked out by anomaly analysis would be most meaningful, if the ancient field has changed only slightly (*e.g.*, due to secular variations) during the cooling history of the volcano. If the cooling history is excessively long and complicated, the direction of TRM may vary in an erratic or too complex manner throughout the volcanic body and the net average magnetization acquired may not be significant. For instance, if the geomagnetic field has reversed several times during the period of acquisition of TRM, one may expect the fields of successive layers or shells magnetized in alternate directions to practically cancel each other. However, the statistical probability of an exact cancellation is very small on account of varying intervals between the major eruptive phases and the different cooling environments of the successive layers. Therefore, residual volcanos as a rule exhibit more or less distinct remanent magnetization and are often used as markers of the ancient geomagnetic field.

Palaeomagnetic aspects of the negative magnetic anomaly

The direction of remanent magnetization worked out earlier by the anomaly analysis can be utilised to calculate the ancient position of a north pole (palaeomagnetic pole) under the assumption that the geomagnetic field was essentially dipolar. The latitude $\varnothing'$ of the virtual palaeomagnetic pole and its longitude λ' can be determined from the knowledge of the declination and inclination of the remanence vector and the geographic coordinates ($\varnothing$, λ) of the Skagerrak anomaly site. The necessary formulae can be found in Chapman & Bartels (1940).

Fig. 4 shows the virtual north pole position determined from the direction of J_r (regardless of the sign of the inclination I). In the equal area projection net is also shown the mean palaeomagnetic pole positions for the European continent since the beginning of the Cambrian. For the

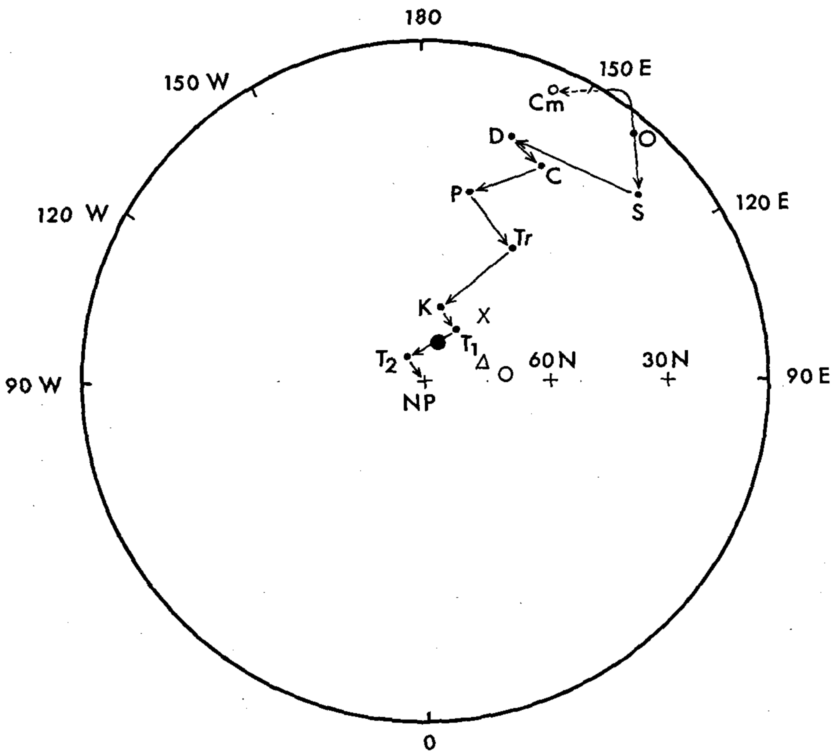

Fig. 4. Palaeomagnetic pole position for the Skagerrak volcano in comparison with some Tertiary poles and mean pole positions since Cambrium for Central Europe (after Irving, 1964).

- ● Tertiary lavas from Faeroes (Abrahamsen, 1967)
- △ Eocene gabbro from E. Greenland (after Irving, 1964)
- o Egersund dolerites, S. Norway (Storevedt, 1966)
- × Skagerrak volcano

sake of comparison known pole positions of Faeroes Tertiary lavas, southern Norway dolerite dykes and of the eastern Greenland Eocene gabbro are also included. It might be seen that the Skagerrak pole position does not fit well with any known directions. Its relative proximity to the lower Tertiary mean pole and also to that of the Eocene gabbro although somewhat apparent, is not close enough to warrant any definite age correlationship. However, if some plausible explanation could be found for the marked deviation of the Skagerrak virtual pole from the Tertiary poles shown in fig. 4, a lower Tertiary age could possibly be proposed for the volcanic mount. One of the possible explanations could be that the eruptive phases and the magnetization process in the submarine volcano taken as a whole has been too complex in a way that the secular variations of the ambient geomagnetic field might not have been averaged out, thus resulting in an angular deviation of about 20° from the mean dipole axis during the lower Tertiary. Another explanation could be that the cooling history of the volcano has been excessively long and possibly associated with a few reversals of the geomagnetic field. This might cause the remanent magnetization to vary in an erratic manner, thus making the assumption of a net uniform magnetization (on which the anomaly analysis is based) not wholly tenable. Still another explanation could be that owing to the relatively sparse aeromagnetic data defining the prominent magnetic anomaly, the direction of J_r worked out from the anomaly analysis might be subject to a considerable error. Unless all of these possibilities can be ruled out, no hypothesis of any tectonic movement of the Skagerrak mount need to be entertained.

Discussion and conclusions

It might be worth to examine the significance of the geophysical findings about the Skagerrak volcano in the light of known volcanics of the neighbouring region. On the basis of palaeomagnetic pole position, no correlation what so ever, could be made with the Egersund dykes of southern Norway which have lately been thought to be of much older age (Storevedt, 1968). The possibility of any correlation with the basalt samples (Noe-Nygaard, 1967) recently dredged by the marine vessel 'Dana' on the southern flank of the Norwegian Deep has also been examined. The laboratory measurements made on a few specimens cut from a dredged basalt sample exhibited an extremely weak remanent magnetization, and as such any palaeomagnetic correlation of the dredged basalt material with the Skagerrak volcano can not be thought of at the present stage.

A correlation of the Skagerrak volcanism with the Eocene ashes of northern Denmark although seemingly apparent from fig. 4 can not be regarded as conclusive unless it is assumed that the noted deviation from the lower Tertiary pole is because of one of the factors mentioned earlier. However, even then the hypothesis of the Skagerrak volcano being the exclusive source of an estimated total of about 180 km³ of ashes scattered over northern Denmark (inclusive of shelf seas) remains to be critically examined. Firstly, it would imply the volcanic eruptions to be excessively violent and a total period of activity lasting over a few million years has to be assumed in order to account for a minimum of three reversely magnetized zones so far found (Sharma, 1969) in the stratigraphical column of ash beds. Secondly, the prominent negative anomaly and the upward inclination (reversed in the normal sense) of the net remanent magnetization would imply an overall greater number of reversely magnetized layers in comparison with the normally magnetized ones. This should be possible to check in the near future by an extensive sampling of the whole series and measuring the samples for the inclination of the remanent magnetization in order to demarcate all the zones of normal and reversed polarity.

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Dansk sammendrag

Afhandlingen giver en kvalitativ tolkning af de forhåndenværende tyngde- og flymagnetiske målinger fra Skagerrak. Både amplituden og formen af tyngde- og magnetiske anomalier viser en mulig beliggenhed af en ret stor vulkanrest ca. 250 m under havbunden dækket af marine sedimenter. Afstanden til grundfjeldet er anslået til ca. 5000 m.

En analyse af den magnetiske anomali viser, at intensiteten af den remanente magnetisme (NRM) er dominerende, og at dens retning er omtrent modsat det nutidige magnetiske felt. Den beliggenhed af den palæomagnetiske pol antydes af retningen for NRM sammenlignet med de i naboregionerne kendte tertiære poler. Sluttelig diskuteres de geofysiske datas egnethed til at korrelere Skagerrak vulkanismen med de eocæne askelag i det nordlige Danmark.

Institut for almen Geologi ved Københavns Universitet,
Østervoldgade 5, 1350 København K., Denmark.
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