Geological implications of mixed oceanic-metalliferous and continental sediments from the Solund–Stavfjord Ophiolite Complex, West Norway

JOHN FRANCIS BOYLE

At one locality the Lower Palaeozoic Solund–Stavfjord Ophiolite Complex is overlain by oceanic metalliferous sediment. Analysis of the composition of this sediment reveals juxtaposition of an active spreading axis and a continental landmass. In contrast to modern mid-ocean ridge sediments a ferro-manganese oxide phase was absent, implying that chemical balances of Mn-nodule related chemical species were very different.

J. F. Boyle, Geologisk Institutt, Avd. A, Allégt. 41, 5007–Bergen, Norway. Present address: Botanisk Institutt, Allégt. 41, 5007–Bergen, Norway.

The Solund–Stavfjord Ophiolite Complex (SSOC) is situated in the Solund–Sunnfjord area in Western Norway (Fig. 1). The SSOC is the youngest dated ophiolite complex in the Scandi-navian Caledonides, based on a U-Pb zircon date of 443 ± 3 Ma (Dunning & Pedersen 1988). A composite terrane, the Sunnfjord melange, provides a terrane link between the continental rocks
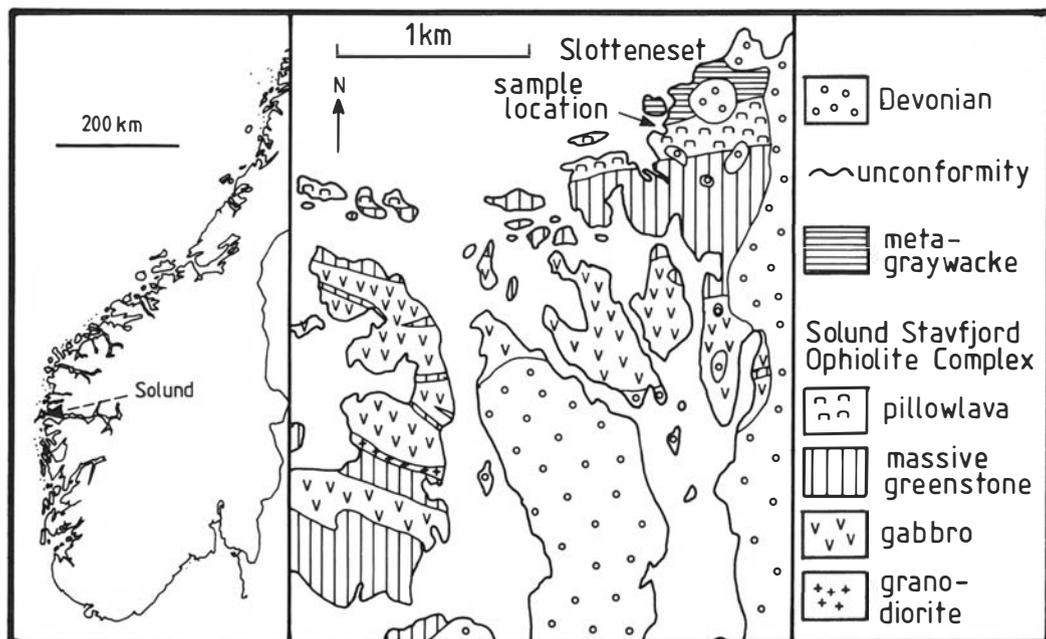

Fig. 1. Geological map of the area showing its location in Solund, close to the mouth of Sognefjord, West Norway (after Furnes 1974). It is part of the Solund–Stavford Ophiolite Complex which outcrops on Solund and a number of islands along the coast to the north.

and the SSOC and shows that the ophiolite accreted onto the continental margin during Silurian time (Andersen et al. in press).

The SSOC comprises mostly sheeted dykes and volcanic rocks (pillow lava, massive sheet flows and hyaloclastite), but high-level isotropic gabbro
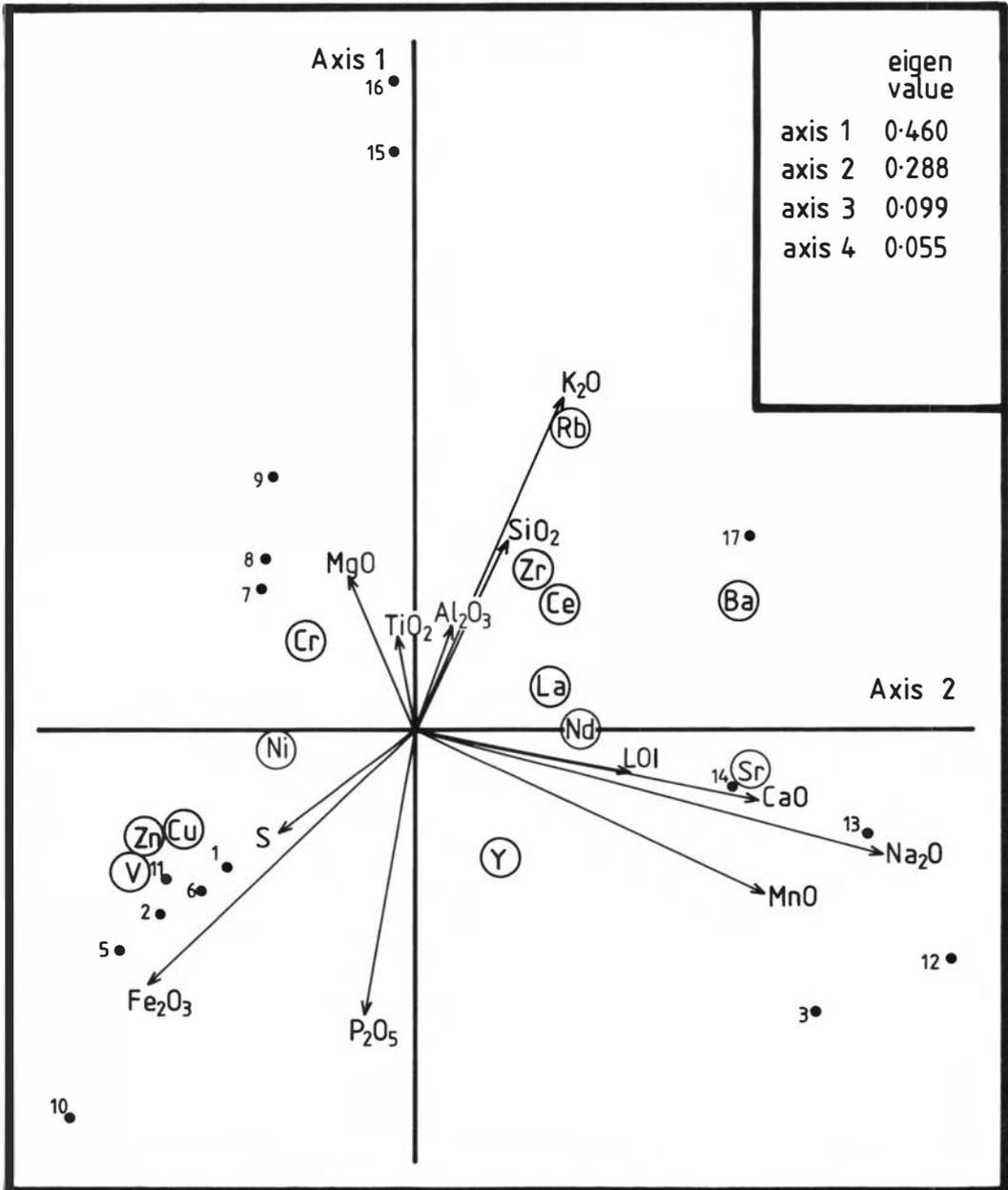

Fig. 2. Principal component biplot of the compositional data. Axes 1 and 2 account for 75% of the variance in the data set, so the biplot gives a good picture of the compositional variation. The major elements lie in three groups: MgO, TiO_2, Al_2O_3, SiO_2 and K_2O; CaO, Na_2O and MnO; and Fe_2O_3, P_2O_5, and S. The samples fall in a triangular field, the apices of which point in the direction of the compositional groups. *Procedure.* The variables were scaled to maximum = 1 in order to reduce magnitude effects without removing differences in relative variability. A covariance principal component analysis was then performed using CANOCO (ter Braak 1987).

and diorite occur in a few places. The metabasalts show evidence of subduction influence (Furnes et al. in prep.).

The cover to the SSOC is a heterogeneous assemblage of sedimentary and volcanic rocks. Above the purely volcanic part of the ophiolite turbidites of both continental and ophiolite derived material are intelayered with ophiolite lava flows. However, at Slotteneset (Fig. 1) a small exposure of *in situ* oceanic sediment occurs sandwiched between the turbidites and the pillow lavas. This sequence, with its contemporary record of the adjacent sediment sources, is thus of considerable interest.

Results

The section of sediment at Slotteneset is 3–4 m thick, located on top of basaltic pillow lavas. It comprises a lower part of black, magnetite-rich schist which grades into an upper part of silty quartzofeldspathic turbidites. The schist is predominantly a dark green/black rock comprising magnetite and Fe-chlorite with minor quartz, spessartine and pyrite. However, there are abundant interlayers, 1–10 mm thick, of paler, silty, material comprising quartz and white-mica, with or without calcite, plagioclase and spessartine. In addition there are a number of beds 5–15 cm thick of massive pyrite. The overlying turbidite is similar to the silty layers, but is coarser and contains more plagioclase and less white-mica.

A section was sampled (16 samples, Fig. 1) and analysed for major and trace elements. A principal component analysis has been used in order to examine compositional variations within the data, and to separate any clearly identifiable compositional components. The results are shown using a covariance biplot (Fig. 2). A biplot shows variables and samples in relation to each other on the same axes (the sum of squared species scores equals the respective eigenvalue, and the sum of squared sample scores equals one). Thus, for example, a sample which is dominated by a particular variable will plot close to that variable. Variables which were actively used in the analysis (the major elements) are shown as arrows. This helps distinguish them, and emphasizes the two main properties of the biplot: the cosine of the angle between two variable arrows indicates the correlation between them; and the length of the arrow is proportional to the variance of that vari-

able. The same properties hold for the passive variables (the trace elements, which are not used in the analysis, but were superimposed on the biplot axes) and the samples.

The biplot reveals three principal variable groupings: K, SiO_2, Rb, Zr, Ce and Ba covary and are negatively correlated with Fe_2O_3, P_2O_5, S, V, Zn and Cu. Perpendicular to this trend lie CaO, Na_2O, MnO and Sr. The samples describe a triangular field stretching in the directions of the compositional groups. By using samples so-16, so-10 and so-12, which are at the extreme corners of the triangle, as end members, a simple model of the data is obtained. The compositions of these samples are shown in Table 1.

Possible sediment sources

The sources of the components can be evaluated by comparison with other sediments of known tectonic setting (shown in Table 1).

End member 1 (Sample so-16) is very similar to average shale. The higher SiO_2 and Zr can be attributed to the silty character. The very low Na_2O indicates a very high degree of maturity. Thus a stable continental source is required.

End member 2 (Sample so-10) in regard to Fe_2O_3, P_2O_5, Cu, Ni, V, and Zn, resembles modern mid-ocean ridge sediment (Table 1). However, there are differences: first, SiO_2, Al_2O_3, MgO, TiO_2, Cr, and Zr are very high; and second, MnO, rare-earth elements (REE) and Ba are too low.

The compositional similarity of the hydrothermal component with modern mid-ocean ridge sediment is evidence for oceanic depths; lower temperature hot springs (which they would have to be at lower confining pressures) have variable, and generally low, trace element contents (Cronan 1980). The compositional uniformity indicates a stable hydrothermal source comparable to modern mid-ocean ridge locations.

The elevated SiO_2 and related elements suggest that a greater proportion of detrital sediment was incorporated into the hydrothermal sediment than is the case for the East Pacific Rise. Given the occurrence of proximal turbidites immediately above the section, implying that land was near by, this is to be expected.

MnO, REE and Ba are dominantly in the ferromanganese component of modern mid-ocean ridge sediments (Chester & Hughes 1969). Their

Table 1. Chemical composition of the Slotteneset sediments compared with average shale and East Pacific Rise metalliferous sediment.

	Slotteneset sediments				Average shale*	EPR met. sed.**
	so-10	so-12	so-16	so-17		
SiO_2	31.76	49.97	64.72	67.04	53.58	11.58
Al_2O_3	8.86	10.18	14.22	8.62	15.47	1.39
Fe_2O_3	44.25	9.05	6.35	3.01	6.76	40.75
MgO	2.29	1.38	3.74	2.11	2.45	1.80
CaO	0.74	11.63	1.17	8.65	3.12	
Na_2O	0.03	0.98	0.06	1.04	1.31	
K_2O	0.12	1.82	3.85	1.49	3.25	0.13
TiO_2	0.41	0.58	0.78	0.45	0.65	0.18
MnO	0.42	2.65	0.26	0.46	0.11	11.10
P_2O_5	0.56	0.58	0.15	0.15	0.17	3.73
S	6.08	0.01	bd	bd		
LOI	4.50	10.07	3.59	7.15		
Total	100.02	98.90	98.89	100.17		
Ba	169	603	495	240	580	2374
Ce	24	76	68	49	59	
Cr	129	98	143	132	90	
Cu	147	12	19	10	45	1200
La	15	51	32	24		88
Nd	16	57	30	26	24	
Ni	107	73	51	26	68	470
Rb	11	87	135	48	140	11
Sr	7	253	31	160	300	
V	324	94	119	60	130	1087
Y	33	59	29	20	26	106
Zn	382	75	120	53	95	380
Zr	118	233	246	196	160	105

bd = below detection. Blank means not determined.
 * Turekian & Wedepohl 1969.
 ** Marchig & Erzinger 1986 (Zn from Bostrøm & Peterson 1969).

absence from the Solund sediment implies either non-accumulation of micro-manganese nodules or post-depositional removal. The presence of beds of pyrite shows that the environment was at least not strongly oxidizing.

End member 3 (Sample so-12) is dominated by CaO, LOI, Na_2O, MnO and Sr. The magnitude of the LOI, and relationship with CaO, is such that calcite must be the dominant mineral. The Na_2O probably occurs in plagioclase, along with some of the CaO. Point counting shows that all the Mn can be accounted for by spessartine.

The accumulation during diagenesis of mixed Mn–Ca carbonate in coarser layers within reducing sediments has been described (Suess 1979; Pedersen & Price 1982; Boyle 1983). If ferromanganese minerals could not form then there would be more Mn available for this process. Transformation of this carbonate to spessartine

could occur at an early stage; formation of garnets at relatively low temperatures has been recorded in ocean sediments (Donnelly & Nalli 1973).

Geological implications

The most important observation is that ocean-ridge type metalliferous sediment, indicating stable, deep-water hydrothermal activity and perhaps active spreading, is intimately mixed with sediments which demonstrate the close proximity of a continental landmass. This is compatible with the suggestion of Furnes et al. (in prep.) that the Andaman Sea, where spreading occurs behind an amagmatic arc, is a possible modern analogue. This would account for the lack of evidence for a magmatic arc (other than the ophiolite itself) and the presence of ophiolite derived volcaniclastics on the ophiolite.

Geochemical implications

If the absence of a ferromanganese component is a general phenomenon, then the geochemical balances of elements which in the modern oceans are strongly influenced by manganese nodules would have been quite different. Either there would have been local oxidized regions particularly rich in manganese nodules, or nodule-related elements would have been distributed more evenly about the oceans. There is evidence for both. Spessartine enrichment is reported from many of the Lower Palaeozoic sedimentary basins of Western Norway (Solli 1981; Brekke 1983; Ingdahl 1985), pointing to greater availability of Mn. On the other hand, a weak negative Ce anomaly is observed in the Solund oceanic sediments (which would be more strongly negative but for the high detrital content); in the absence of manganese nodules there would be no sea-water-Ce depletion.

References

Andersen, T. B., Skjerlie, K. P. & Furnes, H. (in press): The Sunnfjord Mélange; evidence of Silurian ophiolite accretion in the West Norwegian Caledonides. *Journal of the Geological Society of London.*

Bostrøm, K. & Peterson, M. N. A. 1969: The origin of aluminium-poor ferromanganoan sediments in areas of high heat flow. *Marine Geology 7*, 427–447.

Boyle, E. A. 1983: Manganese carbonate overgrowths on foraminifera tests. *Geochimica Cosmochimica Acta 47*, 1815–1819.

Brekke, H. 1983: The Caledonian Geological patterns of Moster and Southern Bømlo: evidence for Lower Palaeozoic magmatic arc development. Unpublished thesis, University of Bergen.

Chester, R. & Hughes, M. J. 1969: The trace element geochemistry of a North Pacific pelagic clay core. *Deep-sea Research 16*, 639–654.

Cronan, D. S. 1980: *Underwater Minerals*, 194–213. Academic Press, London.

Donnelly, T. W. & Nalli, G. 1973: Mineralogy and chemistry of Caribbean sediments. *In* Edgar, N. T., Kaneps, A. G. & Herring, J. R.: *Initial Reports of the DSDP 15*, 929–962.

Dunning, G. R. & Pedersen, R. B. 1988: U/Pb ages of ophiolites and arc-related plutons of the Norwegian Caledonians: implications for the development of Iapetus. *Contributions to Mineralogy and Petrology 98*, 13–23.

Furnes, H. 1974: Structural and metamorphic history of the Lower Palaeozoic metavolcanics and associated sediments in the Solund area, Sogn. *Norges geologiske undersøkelse 302*, 33–74.

Furnes, H., Skjerlie, K. P., Pedersen, R. B., Andersen, T. B., Stillman, C. J., Suthren, R., Tysseland, M. & Garmann, L. B. in prep.: The Solund–Stavfjord Ophiolite Complex and associated rocks, west Norwegian Caledonides: Geology, geochemistry and tectonic environments.

Ingdahl, S. E. 1985: Stratigraphy, structural geology, and metamorphism in the Os area, Major Bergen Arc. Unpublished thesis, University of Bergen.

Marchig, V. & Erzinger, J. 1986: Chemical composition of Pacific Sediments near 20°S: Changes with increasing distance from the East Pacific Rise. *In* Bailey, M.: *Initial Reports of the DSDP 92*, 371–382.

Pedersen, T. F. & Price, N. B. 1982: The geochemistry of manganese carbonate in Panama Basin sediments. *Geochemica Cosmochimica Acta 46*, 56–68.

Solli, T. 1981: The geology of the Torvastad Group: the cap rocks to the Karmøy Ophiolite. Unpublished thesis. University of Bergen.

Suess, E. 1979. Mineral phases formed in anoxic sediments by microbial decomposition of organic matter. *Geochimica Cosmochimica Acta 43*, 339–352.

ter Braak, C. J. F. 1987: *CANOCO- a FORTRAN program for canonical community ordination by [partial] [detrended] [canonical] correspondence analysis, principal components analysis, and redundancy analysis (Version 2.1).* TNO Institute of Applied Computer Science, Statistical Department, Wageningen, The Netherlands.

Turekian, K. K. & Wedepohl, K. H. 1969: Distribution of the elements in some major units of the earth's crust. *Bulletin of the Geological Society of America 72*, 175–192.