A petrographic study on sandstones from the Meluhu Formation, Southeast Sulawesi, Eastern Indonesia

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Abstract: The Meluhu Formation, which is widely distributed in the Southeast Arm of Sulawesi, Eastern Indonesia, is dominated by sandstone intercalated with mudstone, siltstone and shale in the lower part and limestone, siltstone and shale in the upper part. The formation is unconformably underlain by metamorphic complex and unconformably overlain by Palaeogene oolitic limestone strata of the Tampakura Formation.

Petrographic study of 78 selected sandstones and 50 X-ray analyses of shale and siltstone from the Meluhu Formation. Sandstone fragments are dominated by quartz and lithic. The most probable source of the sandstone is a recycle orogen. The source area is likely to have a rugged topography with possible warm climate and high rainfall.

Abstrak: Formasi Meluhu yang tersebar luas di Lengan Tenggara Sulawesi, Indonesia Timur, dikuasai oleh batupasir bersisipan batulumpur, batulanau dan serpih di bagiannya bawah serta batugamping, batulanau dan serpih di bagian atasnya. Formasi ini menindih takselaras batuan malihan dan tertindih takselaras oleh satuan batugamping oolitan dari Formasi Tampakura yang berumur Paleogen.

Petrografi dari 78 batupasir terpilih dan 50 analisa *X-ray* dari serpih dan batulanau dilakukan pada perconto dari Formasi Meluhu. Kepingan-kepingan batupasirnya dikuasai oleh kuarsa dan batuan. Diduga batupasir berasal dari daerah *recycle orogen*. Daerah asal batupasir ini tampaknya mempunyai topografi kasar beriklim hangat curah hujan yang tinggi.

INTRODUCTION

The Meluhu Formation, which crops widely out in the Southeast Arm of Sulawesi (Fig. 1), is unconformably underlain by low grade metamorphics and is unconformably overlain by oolitic limestone strata of the Paleogene Tampakura Formation (Surono, 1994a). Both formations and the low-grade metamorphic basement were named as the Southeast Sulawesi Continental Terrain by Surono (1994a). The Meluhu Formation consists of (from the bottom upward) the Toronipa, Watutaluboto and Tuetue Members. The Toronipa Member is the dominant member in the formation. This member is dominated by sandstone, while the Watutaluboto Member consists mainly of mudstone, siltstone and shale. The Tuetue Member, on the other hand, is characterised by the presence of marl and/or limestone in a sequence alternating between sandstone and mudstone. Depositional environment of the Toronipa, Watutaluboto and Tuetue Members are fluvial, deltaic and shallow marine respectively (Surono, 1994b).

Petrographic analysis of the Meluhu Formation has been carried out on 78 representative thin sections of sandstone and conglomerate (Table 1). These thin sections include 42 from the Toronipa Member, 19 from the Watutaluboto Member and the remaining 17 from the Tuetue Member.

The main aim of the analysis was to determine the sandstone composition in order to interpret the source area character and tectonics. According to Ingersoll *et al.* (1993) third order major rivers, deltas and submarine fans are an excellent predictors of plate tectonic setting. The Meluhu Formation sandstone was deposited in meandering river and tide-dominated delta environments. The samples were all selected from a restricted grain size range of medium sand size to reduce the effect of grain size variation on composition. For these two reasons, the effect of sampling on provenance analysis can essentially be eliminated.

FRAGMENTS

Most of the Meluhu Formation sandstone is grey to dark grey and is composed of 53–82% framework grains (Table 1). The average grain size of the sandstone is 0.42 mm, with a common maximum grain size of 2 mm, but it is pebbly in places. While grain sphericity is moderate, the shape varies from subrounded to well-rounded.

Average composition of the framework grains in the sandstone is 68.2% monocrystalline quartz, 12.7% polycrystalline quartz, 16.6% lithic grains and 1.4% feldspar. Based on the sandstone classification of Folk (1980, Fig. 2), the Meluhu Formation sandstone is dominated by sublitharenite with minor litharenite and quartzarenite.

Quartz

Following the empirical classification of Folk (1980), quartz grains within the Meluhu Formation sandstone can be divided into single or monocrystalline quartz and composite or polycrystalline quartz. Semicomposite quartz of Folk (1980) was classified as composite quartz in this study since it is polycrystalline. Composite quartz grains with a metamorphic texture were counted as metamorphic rock fragments.

The major constituent throughout the sandstone of the Meluhu Formation is monocrystalline quartz. The proportion of quartz in the framework grains varies between 39.2% and 94.8% with a mean of 68.2%. The polycrystalline quartz ranges from 1.4% to 33.0%, with a mean of 12.7%.

Undulose extinction, vacuoles and Boehm lamellae are common features within the monocrystalline quartz. Some fragments have biotite and/or tourmaline inclusions. The quartz fragment shape varies from subrounded to well-rounded with moderate to high sphericity. The presence of embayments, euhedral hexagonal bipyramid crystals and zoned-crystal inclusions within some quartz fragments suggest that these fragments were derived from volcanic rocks (Fig. 3). Most of these fragments have straight-extinction which, according to Scholle (1978), strongly supports this interpretation. Authigenic quartz overgrowths are present on some euhedral hexagonal bipyramid quartz fragments.

Generally, the polycrystalline quartz fragments range from subrounded to well-rounded in shape. The most common extinction is highly undulose (greater than two degrees rotation). This suggests that the composite quartz was mainly derived from metamorphic rocks.

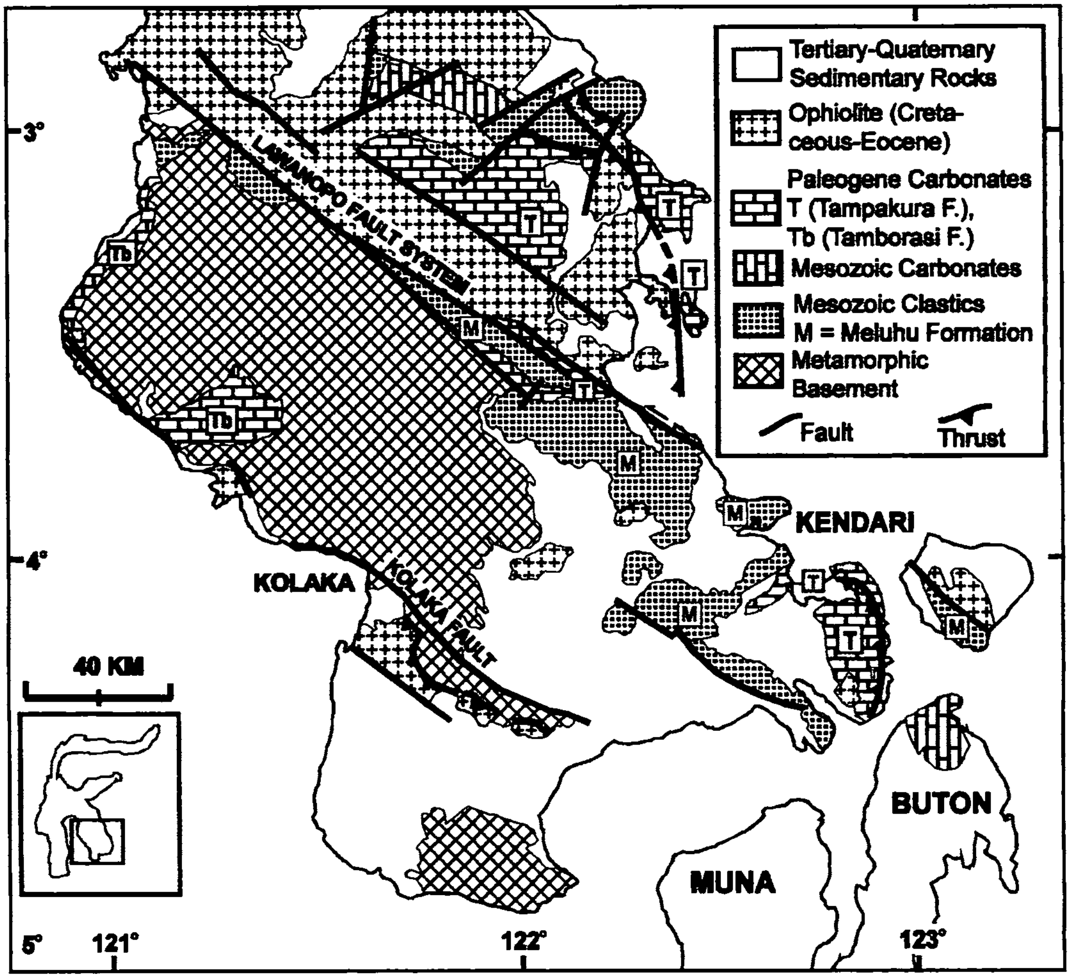

Figure 1. Distribution of the Meluhu Formation in the Kendari area.

Table 1. Petrographic results of sandstones from the Meluhu Formation.

Sample	804	53A	117A	117B	150A	150B	150C	259	261	268	269A	274A	274B	276	277B	280	801	802	803	128A	128B	807	364	368
Location	A2	B0	B0	B0	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B2	B2	B2	B2	B2
Size Average	0.5	0	3	0.8	0.8	0.4	0.2	0.3	0.5	0.2	0.8	0.3	0.3	0.4	0.5	0.2	1	0.8	0.5	1	1	0.5	0.5	0.5
% Matrix	11.2	6	12.3	8.7	24.6	32.7	37.4	18.5	11	9.8	13.6	40.2	8.4	4.7	3.8	8.1	9	4.2	7.4	15.2	18.4	6.3	3.7	5.8
% Mono Qz.	52.7	73	23.7	42.7	27.1	29.2	28.6	60.3	48.4	70.2	46.5	34.3	62.3	54.4	47.1	70.5	42	31.6	59.3	42.9	54.6	47.1	44.4	45.2
% Poly Qz.	7.76	6	5.08	8.58	11.3	10.9	5.08	12.6	10.6	8.54	10.4	13.5	10.9	11.1	10	7.08	8	7.06	11.1	11	13.6	11.3	2.31	8.71
% Feldspar	0	0	0.24	1.44	0.51	1.15	2.42	0.46	0.59	1.01	1.22	1.61	3.38	1.37	1.08	1.88	1	1.35	1.3	2.08	4.4	0	1.01	1.19
% K-feldspar	0	0	0.12	0.36	0.34	0.57	1.31	0.23	0.3	0.51	0.5	0.11	1.9	0.56	0.15	0.85	1	0.61	0.49	1.15	2.46	0	0.51	0.67
% Plagioclase	0	0	0.12	1.08	0.17	0.57	1.11	0.23	0.3	0.51	0.72	1.5	1.48	0.81	0.92	0.17	0	0.74	0.82	0.93	1.94	0	0.51	0.52
% VRF	0	0	4.48	1.44	0	0.86	0.34	0	0	0	0	0.39	0	0	0.38	0	0	0	0	3.58	0	0	1.3	0.3
% MRF	4.85	0	19.2	14.8	10.4	4.3	6.77	3.79	11.3	4.73	11.1	1.39	3.22	8.61	12.3	2.73	10	18.8	1.06	6.16	1.94	10.2	11.3	7.89
% Met.quartz	4.55	0	14.9	11.7	8.32	3.15	6.05	3.79	10.6	4.31	10	1.39	2.39	8.61	11.5	2.73	6	14.4	0	4.37	0.97	7.38	8.08	7
% Schist	0	0	1.94	3.1	1.76	1.15	0.73	0	0	0	1.08	0	0.82	0	0.62	0	2	2.15	1.06	1.72	0.97	0.46	2.6	0
% Slate	0.3	0	2.42	0	0.28	0	0	0	0.67	0.34	0	0	0	0	0.15	0	1	2.22	0	0.07	0	2.36	0.65	0.89
% SRF	9.33	7	7.74	3.03	7.36	4.58	5.03	0	3.11	0	2.44	1.33	2.56	4.83	5.92	2.98	10	8.47	8.72	5.01	0	7.46	11.8	10.7
% Siltstone	7.31	6	6.17	3.03	4.81	2.01	1.79	0	1.85	0	0.5	0.39	0.33	2.01	5.77	2.9	9	6.59	7.5	4.37	0	5.25	9.31	3.65
% Chert	0.9	1	1.57	0	2.26	2.58	2.66	0	1.26	0	1.93	0.94	2.23	2.82	0.15	0.09	1	0.4	0.16	0.43	0	0	1.88	2.09
% Sandstone	1.12	0	0	0	0.85	0	0.58	0	0	0	0	0	0	0	0	0	0	1.48	1.06	0.14	0	2.21	0.65	4.92
% Undif. RF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
% Micas	0	0	0	0	0	0	0.15	0	0.14	0.09	0	0	0	0.16	0.08	0	0	0	0.08	0	0.75	0	0	0.52
% Heavy mins	0	0	0	0.14	0	0	0	0.08	0	0	0	0.08	0	0	0.08	0	0	0	0	0	0	0	0	0
% Other mins	0	0	0	0	0	6.3	0	0	0	0	0	2.95	0.08	0	0	0	0	0	0	0.93	0	0	0	0

Sample	387	391A	396A	398A	400	402	303	308	806	805	408	409	417	428A	442A	442	188A	97	459	460A	461B	468A	475B	72A
Location	B2	B2	B2	B2	B2	B2	C1	C1	C1	C2	C3	C3	C3	C4	C4	C4	E3	E6	E6	E6	E6	E6	E6	E6
Size Average	0.3	0.3	0.3	0.3	0.2	0.8	0.3	0	0.2	0.3	0.5	0.06	0.4	0.05	0.5	0.2	0.4	0.05	0.4	0.3	0.3	0.3	0	0.3
% Matrix	15.2	16.4	11.4	10.3	24.5	7.1	24.5	13	4.8	24.1	6.2	31.4	36.1	13.6	5.8	5.2	4.5	9.1	12.5	23.5	8.2	19.2	21	33.6
% Mono Qz.	45.7	64.3	61.8	56.7	59.3	39.8	48.4	53	70.3	40.3	46.1	53.7	35.6	58.1	44.5	56	71.9	79.5	50.9	46.3	48.7	48.8	47	48.1
% Poly Qz.	13	5.93	6.68	4.72	2.6	5.58	13.2	6	6.81	4.91	3.37	0.88	3.15	26.2	27.4	9.11	6.3	11.4	9	9.3	7.78	10.5	5	7.45
% Feldspar	0.86	0.92	0.16	1.9	3.02	0	0	0	0	0.49	1.29	0.06	0	0	1.59	2.24	0.35	0	1.03	0.56	0.6	0.35	1	0.61
% K-feldspar	0.5	0.54	0	0.46	0.91	0	0	0	0	0.12	0.36	0	0	0	0.59	1.76	0	0	0	0	0.15	0.14	0	0
% Plagioclase	0.36	0.39	0.16	1.45	2.11	0	0	0	0	0.36	0.93	0.06	0	0	1	0.48	0.35	0	1.03	0.56	0.45	0.21	1	0.61
% VRF	0	0	0	0	0	0.42	0	0	0	0	0.57	0	0	0	0	0	0	0	0	0	0	0	0	0
% MRF	2.52	0.15	2.36	3.42	0	15.4	1.06	2	0.17	2.12	8.39	1.26	3.51	0	8.37	1.76	1.22	0	2.95	0.14	5.36	2.23	3	0.06
% Met.quartz	2.52	0.15	1.89	2.36	0	13.6	1.06	1	0.17	1.27	6.88	1.01	1.26	0	7.7	1.44	1.14	0	2.95	0.14	4.64	1.54	3	0.06
% Schist	0	0	0	0	0	0.21	0	0	0	0	1.79	0	2.04	0	0	0	0	0	0	0	0	0	0	0
% Slate	0	0	0.47	0.3	0	1.6	0	0	0	0.85	0.29	0.25	0.21	0	0.67	0.32	0.09	0	0	0	0.75	0	0	0
% SRF	9.5	5.54	7.54	9.13	2.32	7.81	4.02	12	8.87	12.7	11.8	4.4	7.97	1.03	1.17	10.9	6.47	0	9.74	5.94	11.1	8.23	9	4.64
% Siltstone	7.34	5.54	6.13	6.54	2.32	7.53	3.81	11	7.41	11.3	11.3	3.58	5.5	1.03	0.59	10.2	5.95	0	9.08	1.75	8.97	1.54	3	3.42
% Chert	1.08	0	0.16	0.23	0	0.07	0.07	1	0.95	0.3	0.14	0.57	1.57	0	0.59	0.72	0.18	0	0.66	0.28	0	6.7	0	0.73
% Sandstone	1.08	0	1.26	2.36	0	0.21	0.14	1	0.52	1.15	0.36	0.25	0.89	0	0	0	0.35	0	0	3.92	2.09	0	6	0.49
% Undif. RF	0	0	0	0	0	0	3.31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
% Micas	0.36	0.15	0	0.15	0.7	0.7	0.35	0	0	0	0.14	1.26	2.2	0.09	0.08	0	0.7	0	0.15	6.3	1.2	0.56	0	0.18
% Heavy mins	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
% Other mins	0	0	0	0	2.25	0	0	0	0	0	0	1.32	0	0	0	0	0.53	0	0	1.33	0	0	0	0

Table 1. Petrographic results of sandstones from the Meluhu Formation (cont'd).

Sample	72D	72E	73A	74B	91A	91B	92A	92B	94A	317	322	333B
Location	E6	E6	E6	E6	E6	E6	E6	E6	E6	D3	D3	D3
Size Average	0.3	0.4	0.1	0.2	0.3	0.3	0.3	0.2	0.1	0.4	0.3	0.3
% Matrix	26.3	35.4	54.2	9	15	37.8	42.5	21.2	18	10.5	24.4	4.6
% Mono Qz.	48.5	30.4	42.6	43.4	53	38	48.2	46.2	61.6	55.4	45.6	54.4
% Poly Qz.	10.2	7.49	0.94	26.7	4.28	9.13	3.66	8.2	8.73	8.06	7.2	16.9
% Feldspar	1.06	0.77	0.54	0.81	0	0.18	0	0	0	4.99	3.54	3.5
% K-feldspar	0	0.26	0	0.16	0	0.12	0	0	0	1.92	2.89	2.67
% Plagioclase	1.06	0.51	0.54	0.65	0	0.06	0	0	0	3.07	0.64	0.83
% VRF	0	0	0	0	0	0	0	0	0	0	0	0
% MRF	0.2	2.67	0	2.51	0	1.7	0.54	0.4	0	0.92	2.38	2.92
% Met.quartz	0.2	2.46	0	2.51	0	1.7	0.54	0.4	0	0.92	2.38	2.92
% Schist	0	0.21	0	0	0	0	0	0	0	0	0	0
% Slate	0	0	0	0	0	0	0	0	0	0	0	0
% SRF	6.16	9.85	0.36	6.65	13.8	5.54	3.17	11.7	5.44	6.91	5.46	5.59
% Siltstone	6.16	3.18	0.36	4.54	11.2	3.17	1.94	9.47	4.29	5.37	4.18	4.75
% Chert	0	0.15	0	1.95	2.21	1.95	1.24	0.87	1.15	1.54	0.64	0.83
% Sandstone	0	6.52	0	0.16	0.36	0.43	0	1.4	0	0	0.64	0
% Undif. RF	0	0	0	0	0	0	0	0	0	0	0	0
% Micas	0.2	0.1	0.49	0.97	0.21	0.18	0.27	0.13	0.77	0.08	0	0
% Heavy mins	0	0	0	0	0	0	0	0	0	0	0	0.16
% Other mins	0	0	0	0	0	0	0	0	0	0	0	0

Sample	333C	348	350	99B	99C	101A	566A	566B	566C	566D	566E	749
Location	D3	D3	D3	G5	G5	G5	I5	I5	I5	I5	I5	*
Size Average	0.4	0	0.2	2.5	0.2	0.3	0.2	0.3	0.5	0.3	0.3	0.2
% Matrix	8.4	13	35.8	8.1	48.5	38.5	38.3	28.1	11.4	32.1	26	11.7
% Mono Qz.	56.9	51	47.5	33.6	39.7	24.2	33.7	45.3	47.4	35.3	42	52.3
% Poly Qz.	8.24	11	2.5	5.03	2.92	4.14	3.95	9.9	12.5	11.1	12.7	16.9
% Feldspar	3.29	3	1.19	1.11	0.19	1.13	0	0.32	0	0	0.46	1.91
% K-feldspar	2.75	2	0.51	0.46	0	0.45	0	0.32	0	0	0.46	0.32
% Plagioclase	0.55	1	0.68	0.65	0.19	0.68	0	0	0	0	0	1.59
% VRF	0	0	0	1.37	0	0	0	0	0	0	0	1.43
% MRF	2.75	4	0	12.7	0.19	0.9	0	0.19	4.24	2.18	2.47	0.64
% Met.quartz	2.75	4	0	8.3	0.19	0.9	0	0	3.12	1.49	0	0.64
% Schist	0	0	0	3.33	0	0	0	0	1.12	0	2.01	0
% Slate	0	0	0	1.05	0	0	0.35	0	0	0.69	0	0
% SRF	7.22	6	6.19	11.5	4.05	14.5	11.4	7.27	9.97	8.21	6.56	6.21
% Siltstone	5.02	5	3.81	9.86	2.17	11.6	10	6.3	8.26	7.29	2.27	6.21
% Chert	2.2	1	1.36	2.22	1.41	2.79	1.35	0.58	0.45	0.29	1.36	0
% Sandstone	0	0	0.46	0.72	0.47	0.09	0	0.39	1.27	0.63	2.92	0
% Undif. RF	0	0	0	0	0	0	0	0	0	0	0	0
% Micas	0	0	0	0	0	0.14	0.75	1.29	0.3	0.57	0.78	0.08
% Heavy mins	0	0	0	0	0	0	0.15	0	0	0.12	0	0.08
% Other mins	0	0	0	0	0	0	0	0	0	0	0	0

Sample	747	732A	732B	732C	36A	MEAN	SD	MIN.	MAX.
Location	*	*	*	*	*				
Size Average	0.3	0.3	0.1	0.4	0	0.42	0.43	0.05	3
% Matrix	18.4	5.2	34.6	5	2	17.7	12.5	2	54.2
% Mono Qz.	29.3	50	42.2	42.8	55	48.1	11.7	23.7	79.5
% Poly Qz.	5.06	20.3	10.3	18.4	7	9.12	5.27	0.88	27.4
% Feldspar	0	0	0	0	2	1.01	1.12	0	4.99
% K-feldspar	0	0	0	0	1	0.48	0.71	0	2.89
% Plagioclase	0	0	0	0	1	0.53	0.57	0	3.07
% VRF	0.18	0	0	0	0	0.22	0.71	0	4.48
% MRF	0.94	1.57	0.36	6.26	6	4.06	4.63	0	19.2
% Met.quartz	0.12	1.57	0.36	5.24	5	3.33	3.8	0	14.9
% Schist	0	0	0	0.39	0	0.43	0.81	0	3.33
% Slate	0	0	0	0.63	1	0.28	0.54	0	2.42
% SRF	22.9	10.5	5.58	10.2	10	7.02	3.98	0	22.9
% Siltstone	19.3	8.69	5.47	8.13	8	5.33	3.61	0	19.3
% Chert	0.35	0.83	0.12	2.42	2	0.98	1.07	0	6.7
% Sandstone	3.23	0.99	0	0	0	0.73	1.33	0	6.52
% Undif. RF	0	0	0	0	0	0.04	0.38	0	3.31
% Micas	0.06	0.33	0.95	0.16	0	0.35	0.82	0	6.3
% Heavy mins	0.18	0.08	0.06	0	0	0.02	0.07	0	0.4
% Other mins	0	0	0	0.39	0	0.21	1.28	0	9.88

EXPLANATION:

MRF : Metamorphic Rock Fragment
SRF : Sedimentary Rock Fragment
VRF : Volcanic Rock Fragment
Undif. RF : Undifferencied Rock Fragment
SD : Standard Deviation
* : Sample from Labuanbajo Peninsula

Feldspar

Feldspar is present in a number of samples, especially from the southern and central parts of the formation. The range of feldspar content is between 0.1 and 6.5% of the framework grains; the maximum content is in the sandstone from the headwaters of the Lembo River. The feldspar is angular to subangular indicating that it has not travelled far from the source area.

Both K-feldspar and plagioclase can be found in some samples of the Meluhu Formation. Plagioclase was identified by its albite and polysynthetic twinning (Fig. 4). Based on twinning measurements the plagioclase consists of albite, oligoclase and andesine. K-feldspar, on the other hand, is composed of sanidine and microcline. Some samples show a mixture of fresh and weathered fragments of oligoclase. According to Folk (1980) these are indications that the fragments originated from a rugged topography and were deposited in a humid climate. Under such conditions a river can cut through the weathered mantle to the fresh bedrock. Maximum content of plagioclase is 4% and of K-feldspar is 4.5%.

The lateral distribution of feldspar fragments shows that it is more abundant in the southwestern and Kendari areas which were probably closer to the source rocks. Figures 5–6 show that the high content of feldspar relates to a high content of volcanic rock fragments. Because of this, both the plagioclase feldspar and volcanic fragments

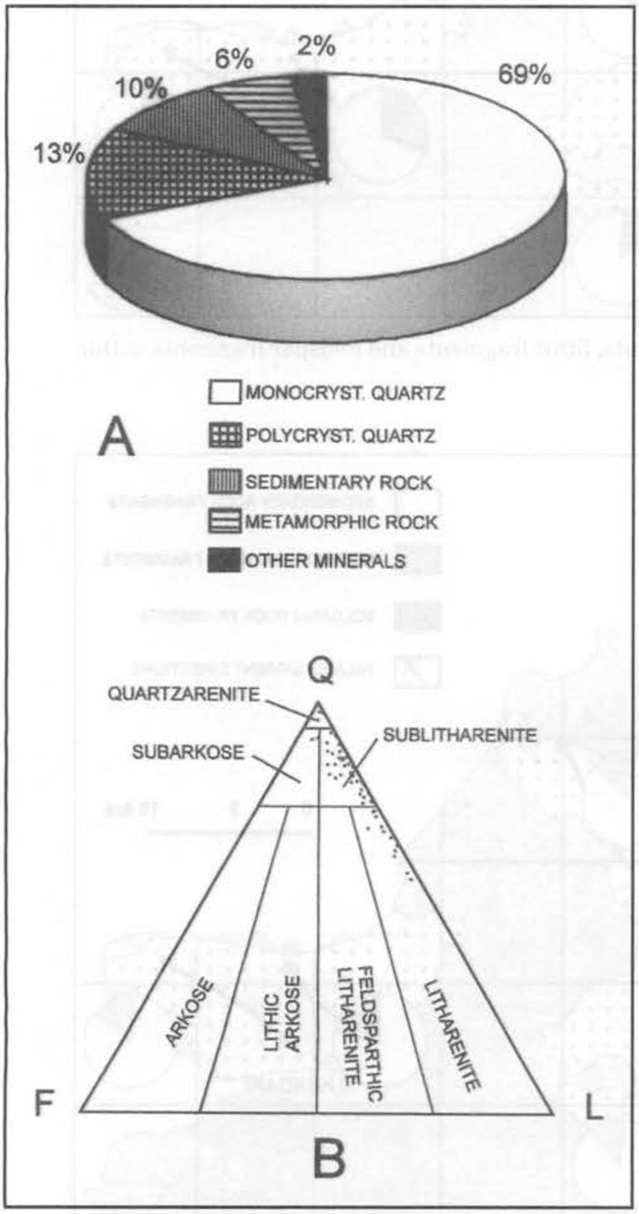

Figure 2. Fragment composition of the Meluhu Formation sandstone, A. Showing monocrystalline quartz is dominant. B. Fragment composition was plotted on triangular diagram of Folk (1980).

Figure 3. Hexagonal bipyramid of quartz fragment surrounded by polycrystalline quartz and phyllitic sedimentary fragments. The hexagonal quartz has embayments and straight extinction indicating the quartz was derived from volcanic rocks.

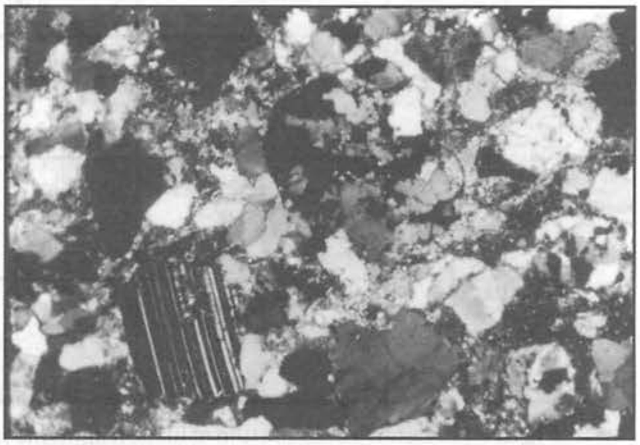

Figure 4. Oligoclase with polysynthetic twinning in the Toronipa Member from Labuanbajo Peninsula.

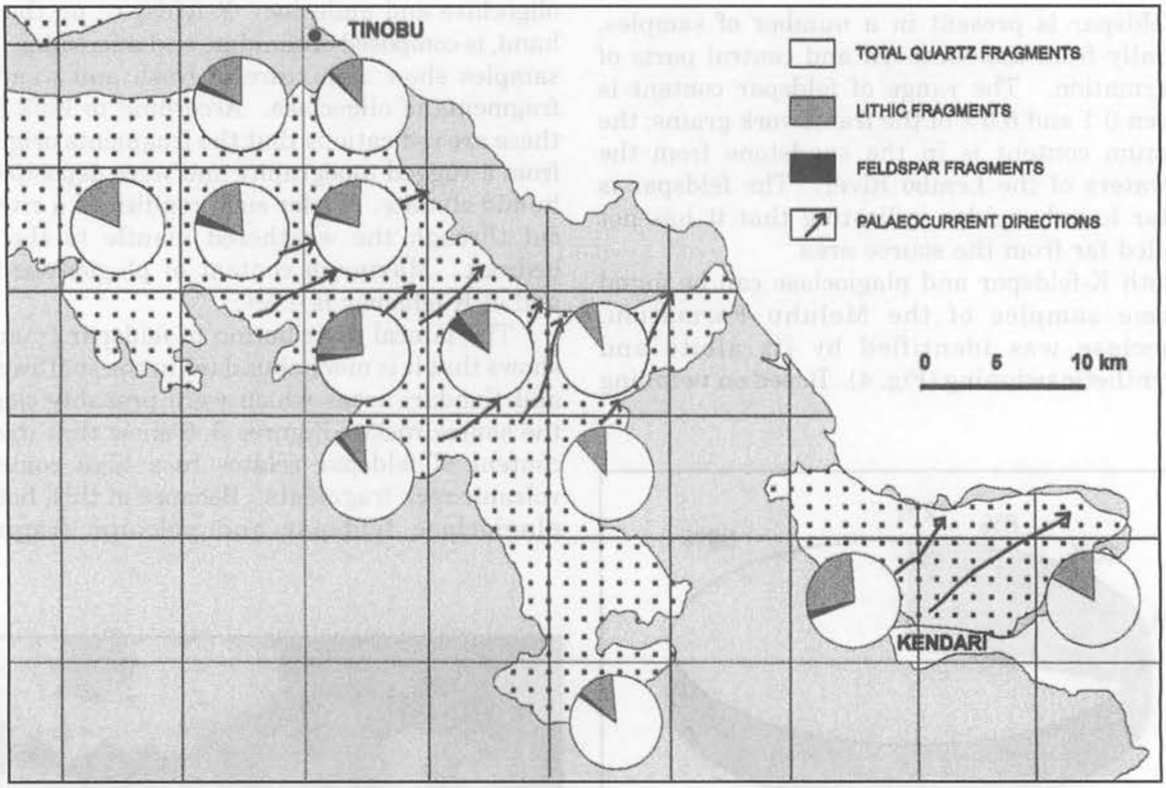

Figure 5. Lateral distribution of total quartz fragments, lithic fragments and feldspar fragments within the sandstone of the Meluhu Formation.

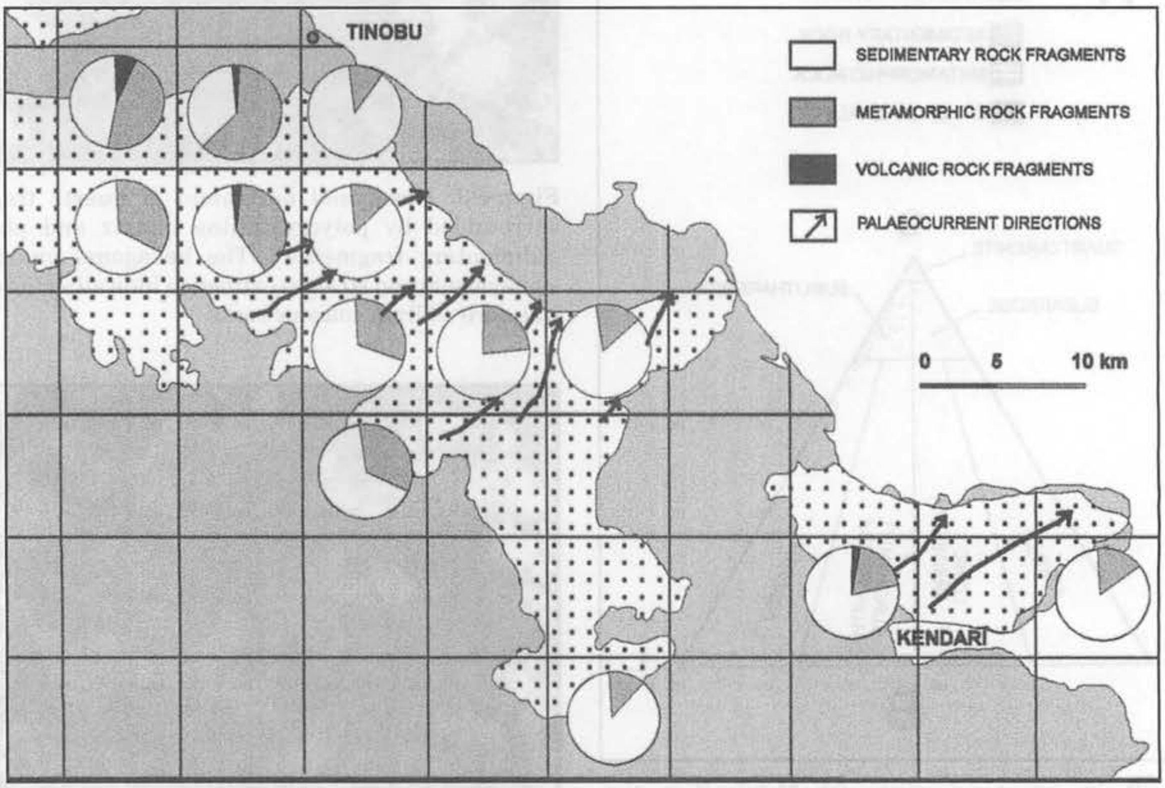

Figure 6. Lateral distribution of lithic fragments in the sandstone of the Meluhu Formation: sedimentary rock fragments, metamorphic rock fragments and volcanic rock fragments.

probably originated from the same source rocks. Based on the feldspar composition which is albite, oligoclase and andesine this volcanic source rock is felsic and/or intermediate. The few weathered igneous fragments, comprising phenocrysts of albite and quartz in a phaneric groundmass (see below), indicate that some feldspar probably originated from granitic rocks.

Rock Fragments

Metamorphic and sedimentary rock fragments were found in each thin section in various quantities, whereas volcanic fragments exist in some samples only. The average rock fragment content for framework grains in the Meluhu Formation sandstone is 16.5%, which consists of 10.4% sedimentary, 5.8% metamorphic and 0.3% volcanic rock fragments. The lateral distribution of rock fragments shows that the average content reduces towards the northeast along the palaeocurrent direction. This suggests that the southern part of the study area was relatively closer to the source of lithic detritus.

The proportion of sedimentary and metamorphic rock fragments are essentially complimentary. The sedimentary rock fragments are reduced when the metamorphic rock fragments increase, and they increase when the metamorphic rock fragments decrease.

Sedimentary rock fragments are the dominant lithic component in sandstone in the Meluhu Formation (7.0%). The fragments consist of siltstone and claystone (5.3%), chert (1.0%) and sandstone (0.7%). Some chert shows included quartz veins indicating that the fragments were lithified before being reworked. It is difficult to distinguish between sedimentary lithic fragments resulting from intraformational erosion and fragments of reworked sedimentary rocks. Lateral distribution of rock fragments shows that the percentage of sedimentary rock fragments increases towards the northeast. Some fine-grained sedimentary rock fragments show they were still semiplastic when deposited. This evidence suggests that sedimentary rock fragments derived from intraformational erosion are dominant in the Meluhu Formation sandstone, especially in the northeastern area where the depositional energy level was lower. However, the well-rounded shape of the remaining sedimentary fragments and their relatively similar size to other fragments, suggests that these fragments probably originated from an older sedimentary terrane.

Metamorphic rock fragments are the second most important lithic component in sandstone from the Meluhu Formation (5.8%). The fragments, which are generally platy, are composed of metaquartzite (4.8%), quartz-muscovite schist (0.6%, Fig. 7) and slate (0.4%).

Stretched metamorphic quartz fragments have been recognised within a few samples. Individual quartz crystals in the fragments have strongly undulose extinction with crenulated and/or granulated borders. Stretched metamorphic fragments indicate that the source region contained quartz-bearing rocks that were sheared or strained without extensive recrystallization (Folk, 1980).

The lateral distribution of the metamorphic rock fragments shows that their percentage decreases along the palaeocurrent direction, i.e. to the northeast. This is probably because the metamorphic fragments became weathered and reduced to single mineral grains during transportation.

A few samples contain a small number of volcanic rock fragments. The volcanic fragments are most commonly preserved in conglomerate and coarse-grained sandstone and vary in abundance from 0.1% to 7.4%. The fragments are subangular-angular in shape and highly weathered in some places. They differ from the other fragments in the samples which are commonly rounded to well rounded. Because of this, the volcanic fragments were probably transported less distance from the source rocks than the other fragments. The lateral distribution of volcanic fragments is irregular. A thin sequence of volcanic rocks probably covered the metamorphic rocks in the source area and/or occurred as small dykes or sills in the metamorphic terrane, as observed in the Ranteangin River (Surono, 1986).

Tuff fragments have been identified in some thin sections from surrounding Kendari. The fragments consist of fine-grained tuff with scattered feldspar and quartz crystals. Low angle-albite twinning in the plagioclase and the existence of

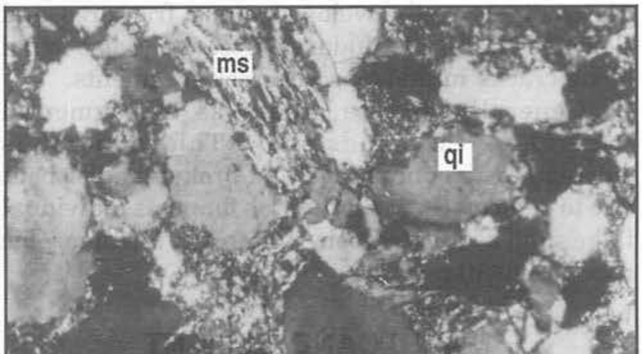

Figure 7. Plagioclase (p), zoned inclusions in quartz (qi) and mica schist (ms) fragments in the Toronipa Member. Sample was taken from the Andomowu River, Tinobu.

quartz in these fragments suggest a dacitic composition. Some tuff fragments have quartz veins indicating that lithification and deformation took place before the fragments were reworked. Therefore, the tuff fragments are epiclastic or redeposited volcanic rock fragments.

Some samples from the headwaters of the northern part contain a few weathered igneous fragments comprising phenocrysts of albite and quartz in a phaneric groundmass. These igneous fragments were probably derived from felsic and/or intermediate intrusive rocks (especially granite) as observed along the Ranteangin River by Surono (1986).

Heavy Minerals

Heavy mineral content within the Meluhu Formation is less than 1%. Dark brown tourmaline is the most common heavy mineral within the Toronipa Member. According to Blatt *et al.* (1980) and Pettijohn (1975), dark brown euhedral tourmaline is probably derived from metamorphic rocks.

Zircon is characterised by a very high relief, the presence of numerous inclusions and straight extinction. It is commonly rounded to well rounded in shape, which is probably an indication that it was reworked from earlier sequences. The occurrence of zircon in a metasiltstone lithic fragment within a sandstone sample taken from the Andomowu River strongly supports this interpretation.

Mica

The most common mica within the Meluhu Formation sandstone is muscovite, whereas biotite is less abundant. Two types of muscovite were recognised in the sandstone. Primary muscovite occurs as individual flakes that commonly have been broken or bent due to compaction. Secondary muscovite is well-developed along fractures and cleavage planes. Secondary muscovite is also found along cracks in feldspar and rock fragments.

Generally, biotite occurs as a fragmental mineral in the sandstone. This mineral is subangular to subrounded and broken and/or bent due to deformation. Biotite was found as individual flakes and as an accessory mineral in metamorphic rock fragments.

MATRIX AND CEMENT

All material finer than 35 microns in the sandstone is termed detrital matrix. Generally, the matrix content in the Meluhu Formation sandstone is less than 10%.

The main primary cement in the Meluhu Formation sandstone is silica, with some carbonate in a few samples. The most common silica cement is chert. Quartz overgrowths occur in few samples. Quartz cement and fibrous chalcedony have been found most commonly in coarse-grained sandstone and conglomerate. Secondary cements consist of iron oxide and calcite.

Secondary carbonate cement occurs in some samples, consisting of micrite and spar calcite. Calcite cement-filled fractures and pores in sandstone, which is otherwise cemented by silica, indicates that the calcite cement post-dated compaction and fracturing. Samples which have secondary carbonate cement were taken from areas close to the covering limestone units of the Tampakura Formation and Pohara Limestone. Thus, the carbonate-rich liquid probably originated from the Tampakura Formation and Pohara Limestone and moved down into the Meluhu Formation after deformation associated with the collision and ophiolite emplacement during the Late Oligocene and Early Miocene.

Iron oxide cement was found in some sandstone samples from the headwaters of Andomowu River. The average content is less than 8%. The cement had completely replaced some lithic fragments, matrix and previous cements in a few samples. Some quartz grains are "floating" in the ferruginous cement, but originally the fragments were grain supported since a few concavo-convex and sutured contacts still remain. This evidence suggests that the iron oxide is a secondary cement replacing previous cement, matrix and some fragments. Caries texture (Boggs, 1992) in some samples strongly supports this interpretation. The volcanic rock fragment content in the headwaters of Andomowu River is higher than in other areas. Most of the remaining lithic fragments are very altered. The source of iron-rich water which formed the iron oxide cement was probably derived from the volcanic rock fragments and/or iron-rich surface water.

CLUSTER ANALYSIS

Correlation coefficient and cluster analyses were undertaken on the petrological sandstone data from the Meluhu Formation. Computations were carried out using a program modified from Jones and Facer (1981). The initial analyses used all 41 petrological variables, but the number of variables was later reduced by eliminating the least significant variables. The most significant result is the model that used 18 variables as shown in Figures 8–9.

Five significant groups resulted from the cosine-theta similarity coefficients in the Q-mode analysis (Fig. 8). Group I is characterised by a high

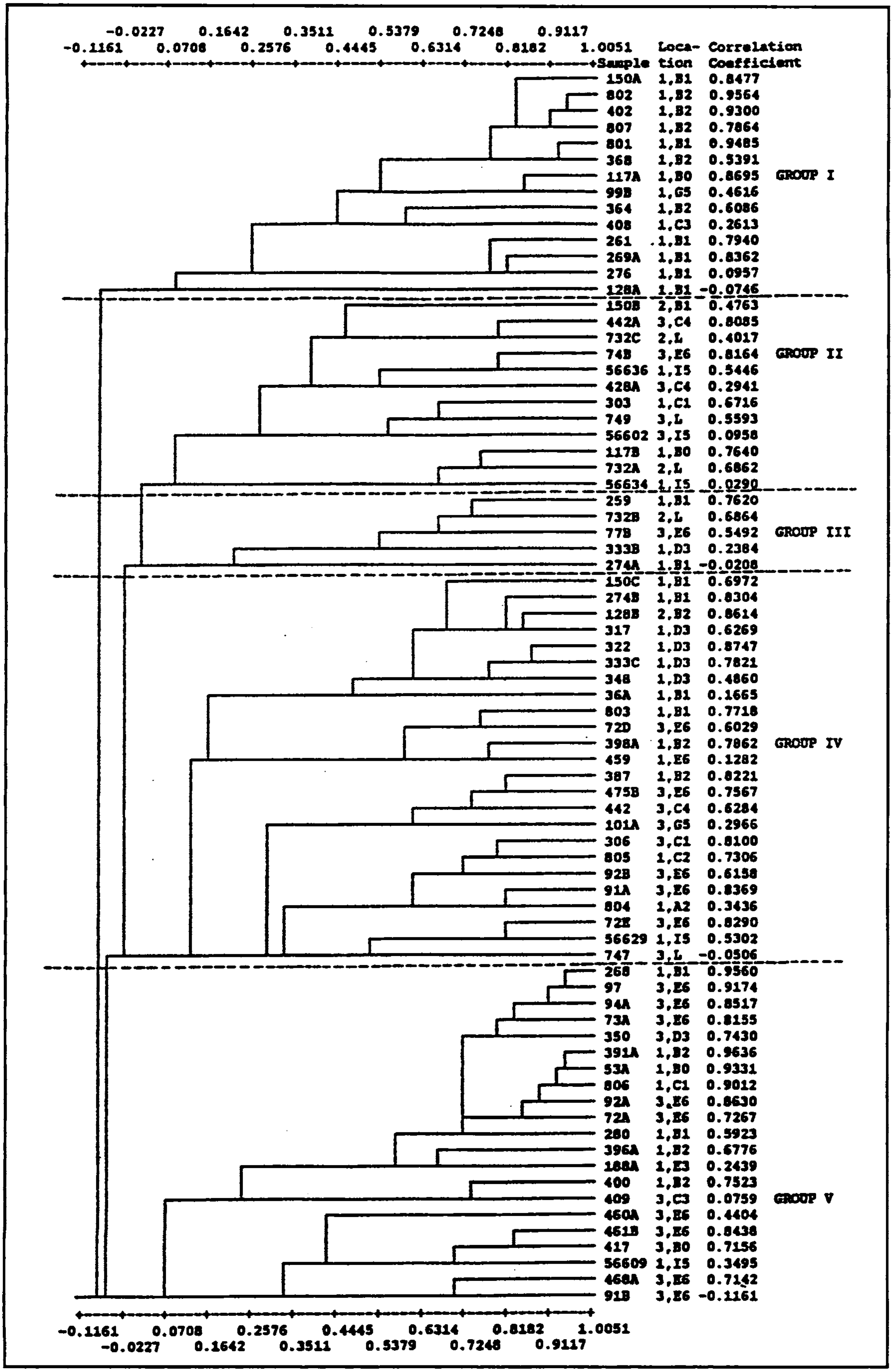

Figure 8. Q-mode dendrogram of petrographic data from the Meluhu Formation. For location see Figure 7, (1) Toronipa Member, (2) Watutaluboto Member and (3) Tuetue Member.

percentage of metamorphic and volcanic rock fragments with averages of 16.8% and 1.3% respectively. All of these samples came from the Toronipa Member sandstone in the northwestern area. Most of samples in Group II are from the Toronipa, Watutaluboto and Tuetue Members on the Laonti Peninsula. Group II is characterised by a high polycrystalline quartz content (26.8%). No significant area or member can be described for the samples in Group III. However, monocrystalline quartz and feldspar are relatively high in Group III. Group IV samples contain high percentages of feldspar (2.3%) and sedimentary rock fragments (14%) and represent 58% of the Toronipa and 38% of the Tuetue Members in the southeastern area. The last group (Group V) has a high percentage of monocrystalline quartz (79%) but a low percentage of polycrystalline quartz (8.8%) and represents the Tuetue Member (61%). The Group V samples are also from southeastern area.

Because of its stratigraphic position, Group I, which represents the oldest member of the Meluhu Formation (Toronipa Member), is characterised by a high content of the metamorphic rock fragments. Group II and Group IV are from parts of the Toronipa, Watutaluboto and Tuetue Members that, stratigraphically, come from the middle of the formation. Group II and Group IV are characterised by high content of sedimentary rock fragments, feldspar and polycrystalline quartz. Group V represents at the upper part of the formation that is dominated by monocrystalline quartz. These significant features confirm that the quantity of rock fragments and unstable minerals (e.g. feldspar) decrease upwards. This was probably caused by a reduction in transportation energy due to a reduction in relative source area elevation and to the transgressive process during the deposition of the Meluhu Formation. Samples located in Group IV and Group V are from the northwestern and southeastern regions respectively. In general, similarity of petrographic data clusters is influenced by both the stratigraphic position and the geographic location of the sample. This means that the sandstone composition varies in both vertical and horizontal directions.

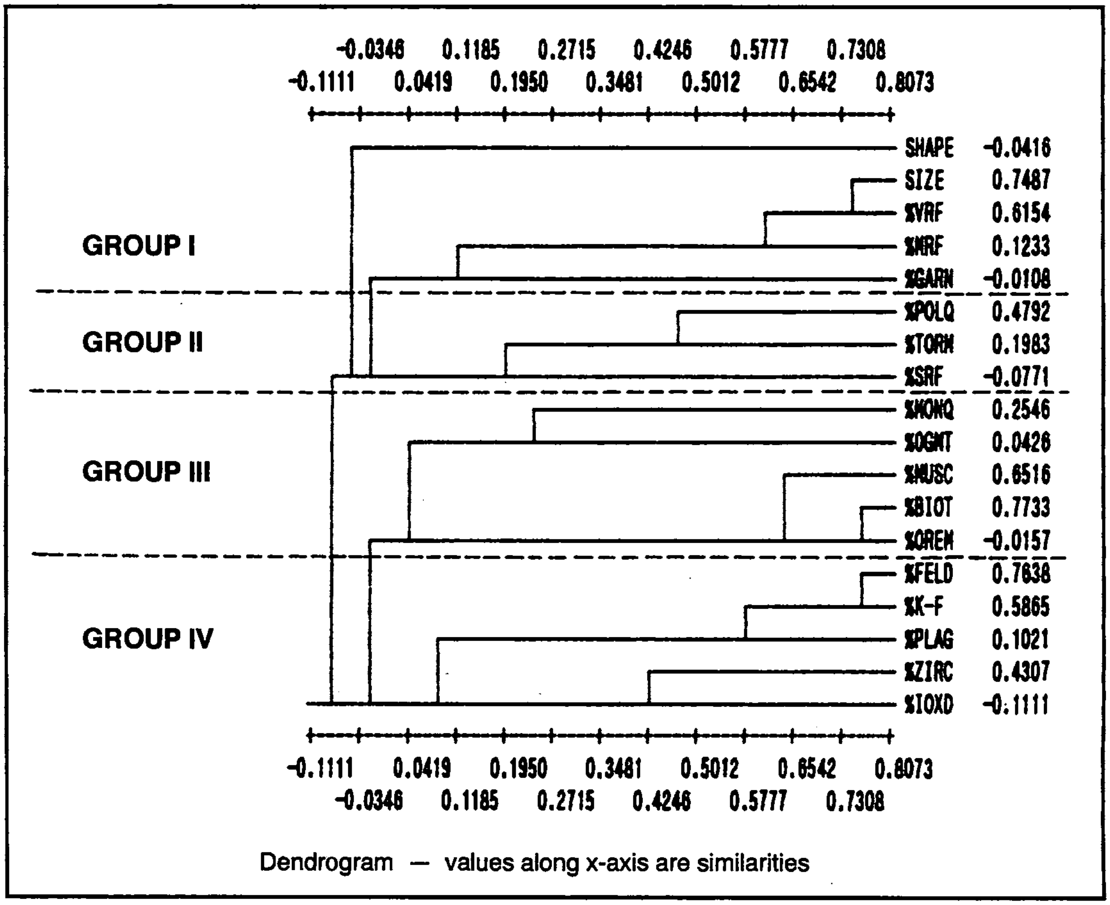

Figure 9. R-mode cluster diagram of fragment composition within the Meluhu Formation (VRF) volcanic rock fragments, (MRF) metamorphic rock fragments, (GARN) garnet, (POLQ) polycrystalline quartz, (TORM) tourmaline, (SRF) sedimentary rock fragments, (MONQ) monocrystalline quartz, (OGMT) organic matter, (MUSC) muscovite, (BIOT) biotite, (OREM) ore mineral, (FELD) feldspar, (K-F) K-feldspar, (PLAG) plagioclase, (ZIRC) zircon, and (IOXD) iron oxide.

The R-mode cluster analysis diagram using 18 variables can be divided into four groups (Fig. 9). In Group I, average of grain size, and volcanic and metamorphic rock fragments are closely linked together. Petrographic results show that both the volcanic and metamorphic rock fragments increase in abundance in the coarser sandstone samples, especially in the northwestern area. This is caused by the effect of transportation whereby the rock fragments were broken down (disaggregated) during transportation. In Group II, polycrystalline quartz is positively correlated with tourmaline and sedimentary rock fragments. With the exception of the sedimentary rock fragments, samples, which consist of polycrystalline quartz and tourmaline, were taken from the southern area which is close to the metamorphic source rocks. This suggests that the polycrystalline quartz and tourmaline were probably derived from the same metamorphic rocks. Muscovite and biotite are also closely correlated with ore minerals in Group III. With the exception of the ore minerals, the muscovite and biotite are likely to have a similar source. K-feldspar and plagioclase are strongly correlated with total feldspar, as expected, forming a subgroup in Group IV. These minerals may be derived from the same source or simply reflect proximity to a granitic and volcanic source, respectively. Zircon and iron oxide are linked in another subgroup. The zircon and iron oxide only occur in southwestern and Watutaluboto areas and probably indicate the effects of intense weathering.

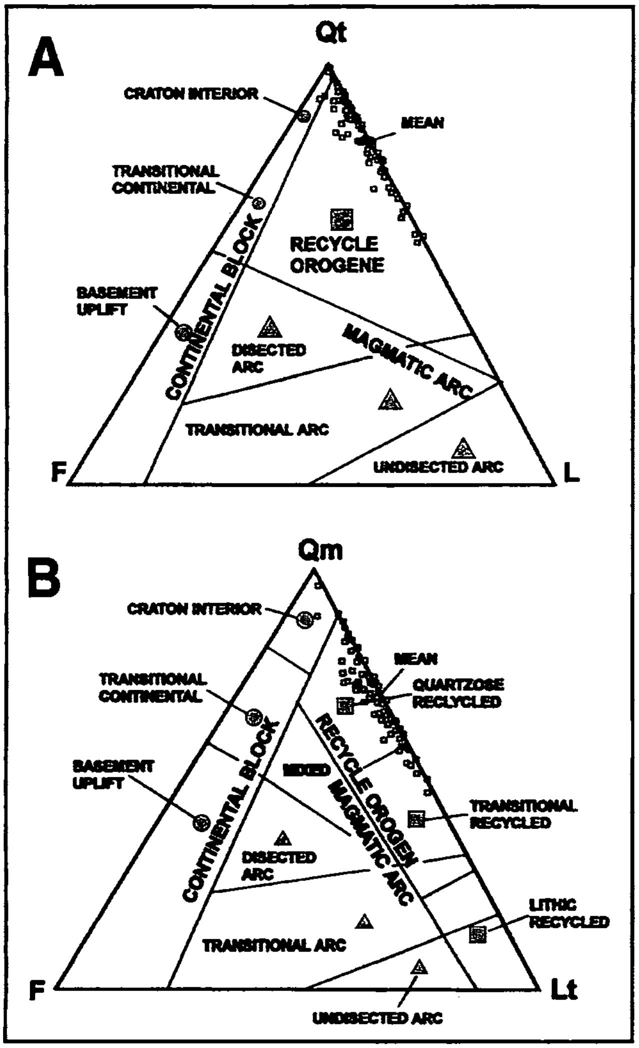

Figure 10. Plotting fragment composition of the Meluhu Formation on triangular diagrams of Dickinson and Suczek (1979 modified by Dickinson *et al.*, 1983); F (feldspar), L (lithic), Lt (total lithic including polycrystalline quartz), Qm (monocrystalline quartz) and Qt (total quartz). Plotting data from the Meluhu Formation sandstone shows the sandstone was derived from a recycle orogen.

PROVENANCE

Provenance studies using sedimentary petrology aim to identify the nature, composition, identity and dimension of the source rocks, the relief and climate in the source areas, and the effect of transportation (Basu, 1985). Knowing the composition of a sandstone is a major guide for its provenance interpretation. Sandstone composition is controlled by climate, relief of source area, transport and depositional processes and process after deposition (Zuffa, 1985). In this provenance study all modal composition data were recalculated as volumetric proportions of fragments (Dickinson and Suczek, 1979).

Using the triangular FQtL diagram (introduced by Dickinson and Suczek, 1979, modified by Dickinson *et al.* 1983a) suggests that the Meluhu Formation sandstone was derived from a recycled orogen (Fig. 10A). Variation within the recycled orogen provenance is not clearly pointed out by the FQtL diagram, because many lithic chert fragments plot together with quartz at the same pole (Dickinson *et al.*, 1983). However, in general, most foreland-uplift provenances fall close to the Qt pole whereas subduction complex provenances are clustered near the L pole (Dickinson and Suczek, 1979). The mean of the Meluhu Formation sandstone is much closer to the Qt pole rather than the L pole.

Plotting the framework grain composition of the Meluhu Formation sandstone on the FQmLt ternary diagram of Dickinson and Suczek (1979, modified by Dickinson *et al.*, 1983) also culminated in a recycled orogen source (Fig. 10B). The samples mainly plotted around the quartzose recycled point of the FQmLt diagram. A few samples plotted within the craton interior-continental block provenance on both the FQtL and FQmLt diagrams.

However, the mean of the sandstone composition from the Meluhu Formation plotted within the field of a quartzose recycled provenance.

Using the LvLmLs ternary diagram of Graham *et al.* (1976, modified by Ingersoll and Suczek, 1979) the mean of the Meluhu Formation sandstone falls in the area of suture belts and rifted continental margins. The mean of the Meluhu Formation sandstone is closest to the mean of the rifted continental margins. Thus, a rifted continental margin source may represent an alternative provenance for the sandstone in addition to the recycle orogen source.

Using the LvQpLs diagram of Dickinson *et al.* (1983), the sandstone in the Meluhu Formation was derived from collision suture or fold-thrust belt sources (Fig. 11). The PQmK diagram of Dickinson *et al.* (1983), on the other hand, shows the sandstone to have been derived from a continental block provenance. Because of the low content of feldspar and volcanic rock fragments within the sandstone, they plot near the Qt-L, Qm-Lt and Qp-Ls lines. The figures suggest that these sandstone samples were derived from a fold-thrust system of indurated sedimentary and low-grade metamorphic rocks.

The features above suggest that the most probable source for sandstone within the Meluhu Formation was a recycled orogen. The low-grade sequence of metasediments at southwest margin of the basin was the most likely provenance area for the formation. The metamorphic terrain was intruded by aplitic rocks as reported by Surono (1986) along the eastern coast of the Bone Gulf.

In a recycled orogen, the relative proportion of stable quartz fragments and unstable lithic fragments is highly variable (Sutner *et al.*, 1981). Modern sands which have originated from such regions have Qt/L ratios between about 3:1 in *humid* areas and about 1:3 in semi-arid areas. The average Qt/L ratio within the Meluhu Formation is 6:1.

X-RAY DIFFRACTION (XRD)

X-ray diffraction (XRD) analyses were carried out using a Phillips PW 1130/90 generator, copper radiation, a graphite monochromator and a scan speed of $^1/_2$° 2θ/min. Analysed samples from the Meluhu Formation consist of 40 samples from the Toronipa Member, 3 from the Watutaluboto Member and 7 from the Tuetue Member. The samples are mudstone, shale and fine-grained sandstone. All of the samples were prepared as clay mounts on ceramic discs and were analysed in an untreated state. Twenty seven of them were analysed after saturation with ethylene glycol and rerun after being heated for one hour at 550°C. The analytical results are tabulated in Table 2.

Illite, muscovite and kaolinite are the most common clay minerals within the Meluhu Formation (Fig. 12). Illite has been found in all of the examined samples. Muscovite and sericite are the most common minerals in the fine-grained sandstone.

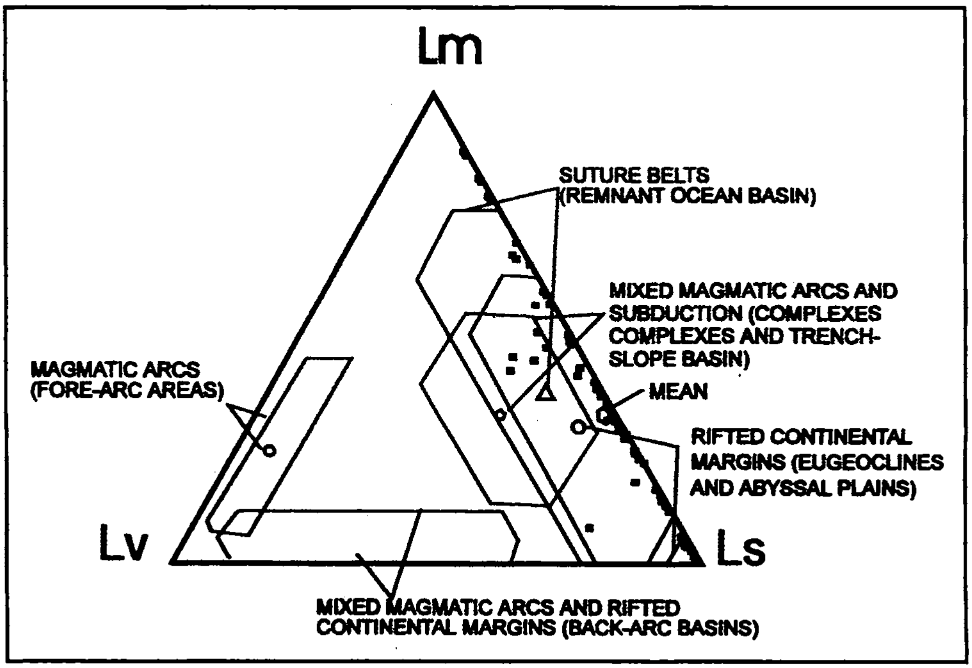

Figure 11. Sandstone fragment composition of the Meluhu Formation plotted on LvLmLs diagram of Ingersol and Suczek (1979). (Lv) volcanic lithic fragment, (Lm) metamorphic lithic fragment and (Ls) sedimentary lithic fragment.

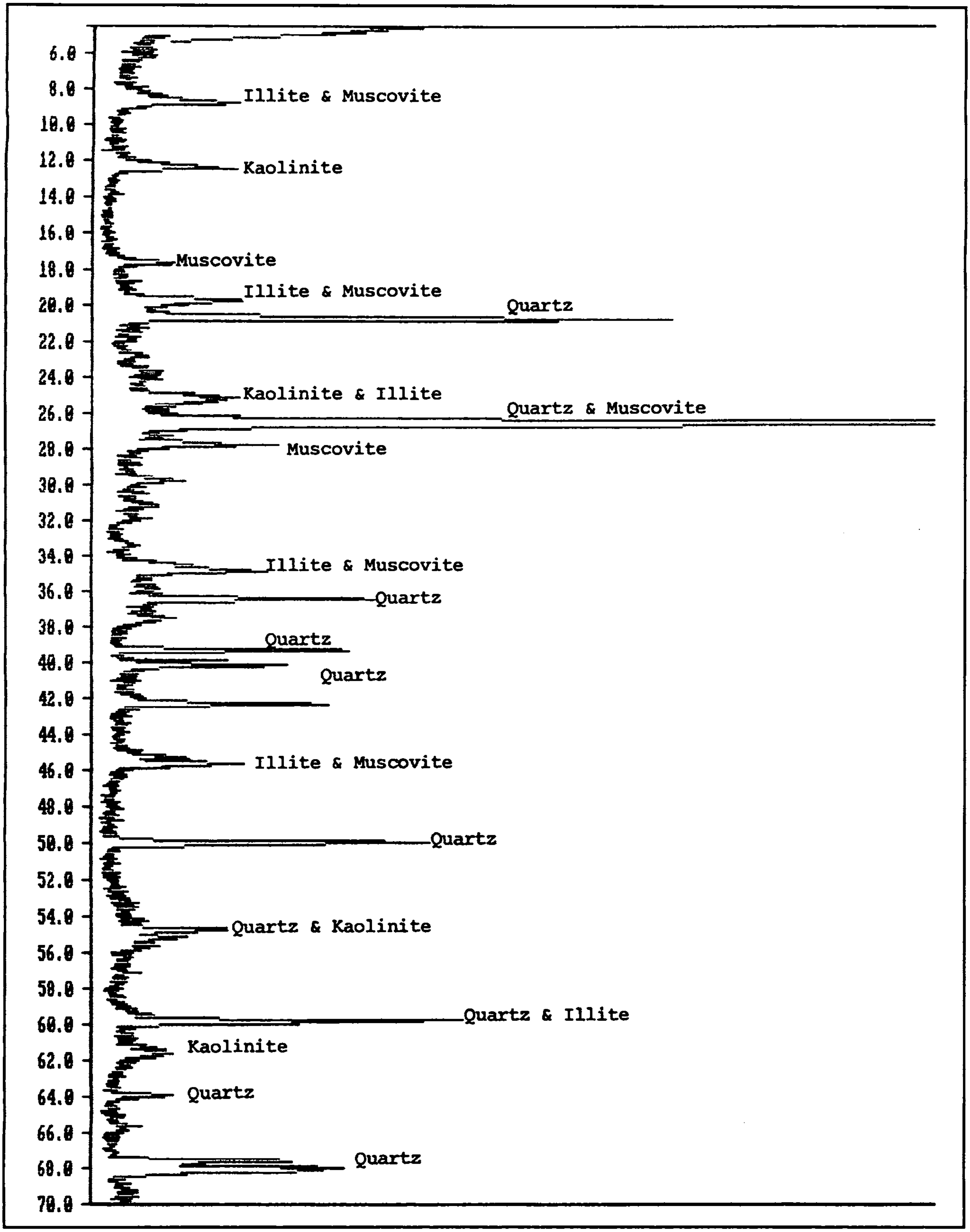

Figure 12. XRD trace of the Toronipa Member sandstone, sample from Kendari city.

Table 2. X-Ray analyses of the fine-grained sediments from the Meluhu Formation.

SAMPLE	81A	98	98B	99C	128A	147A	186B	186	196A	239	268	274	274J	277A	280	301	301A	305	322	333B	358	390A	391A	396A	398A
SUBUNIT	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.
QUARTZ	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
SEPIOLITE			R			R	R	R	R	R						R	R		R		R				
KAOLINITE	M	M	R	M	M	R(H)	M(H)			M	R	R(H)	R	R	R	M	R				R(H)	R	R	R	R
CHLORITE		R(V)						R																	
ILLITE	R	M	R	R		M	R			M	R			A		M	M	A	R			M			R
MONTMORIL.			R														R	M					R		R
SERICITE			R		R										R							R			R
CALCITE	R				R								R		R						R				
MUSCOVITE	M	M	M	M	R	M	R		R			R		M			R	M	R					R	
BIOTITE				R			R				R		R		R										
PHLOGOPITE					R					R			R												R
ALBITE									R		R		R						R	R			R	M	
SANIDINE											R							R		R					
ORTHOCLASE				R								R		R	R				R			R		R	R
MICROCLINE																									

SAMPLE	400	407	411	413	472	474	475A	480	506	523	724B	724C	724D	724G	724L	725D	48C	72E	111B	417	454A	460	461	748C	781A
SUBUNIT	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Tr.M.	Wt.M	Wt.M	Wt.M	Tt.M.	Tt.M.	Tt.M.	Tt.M.	Tt.M.	Tt.M.
QUARTZ	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
SEPIOLITE				R	R			R							R		R							R	
KAOLINITE	R	M	M	M	M	R	R	M		M	M	M	M	M	R	M	R	R	R	R(H)			M	M	M
CHLORITE																					R	R			
ILLITE	R	M	M	M	A	M	M	R		R						A	R				R	M	M	A	R
MONTMORIL.		R	M	R	M	M		R	M	R	R	R	R	R	R	R	R			R	M	R	M	M	R
SERICITE					R			R							R					R					
CALCITE									A		R	A	A	A	R				A		A				R
MUSCOVITE	R	M	M	M		M	M			M		R		M	R	M	M	R				M	M	M	M
BIOTITE									R						R			R			R				
PHLOGOPITE			R									R	R							R					R
ALBITE	R					R					R	M	M	M									R		
SANIDINE																									
ORTHOCLASE					R		R		R					R		R	R	R							
MICROCLINE																			R				R		

EXPLANATION: A=ABUNDANT, M=MODERATE, R=RARE; H=HALLOYSITE, V=VERMICULITE; Tt.M.=TUETUE MEMBER, Wt.M.=WATUTALUBOTO MEMBER; Tr.M.=TORONIPA MEMBER

Illite and Muscovite

Distinction between illite, sericite and muscovite using XRD techniques is difficult because their peaks are close each other. In the Meluhu Formation both minerals can be found.

The most common clay mineral in the Meluhu Formation is illite. The major factors which influenced the clay suite transported by a river are relief, elevation, source rocks, river length and flood periodicity (Weaver, 1989). Konta (1985) studied suspended minerals from 13 big rivers in the world. In his conclusion most rivers contain illite-mica with minor chlorite and kaolinite. Kaolinite is only dominant in tropical rivers.

The degree of metamorphism can be related to the sharpness and width of the 10Å illite peak as studied by Weaver (1960). He measured the peak character of illite which he called the sharpness ratio (SR) or the Weaver index (WI). The average WI of the Meluhu Formation is 2.61 indicating that the formation shows incipient to weak metamorphism or anchizone metamorphism. However, the explanation of Weaver (1989) suggested clearly that the anchizone occurs within the WI range of ~2.3 to ~10. Thus, the Meluhu Formation lies only just above the diagenetic stage.

Kubler (1968) also used the illite peak for measuring the degree of metamorphism or crystallinity. He measured the peak-width at half-height (in mm) giving what he called the crystallinity index (CI) or Kubler index (KI). Later, Weaver (1989) agreed that using the KI is a more precise and easier measure than the WI. By using a scan speed of 2°/min and a chart speed of 1,600 mm/hr, as suggested by Weaver (1989), the average KI of the Meluhu Formation illite is 5.16 or in the diagenetic stage.

The average degree 2θ crystallinity of the Meluhu Formation samples of 0.55 also shows that the formation is still in the zone of diagenesis. This result is strongly supported by the vitrinite reflectance rank of 0.48 $R_v$max to 0.82 $R_v$max (Surono, 1994b).

Kaolinite

Kaolinite is the second most common clay mineral within the Meluhu Formation. Kaolinite and chlorite both have 7Å reflections in untreated samples. After heating, the kaolinite 7Å reflection disappears whereas chlorite, which is less affected by heating, still retains some 7Å reflection and has an enhanced 14Å reflection (Lindholm, 1987).

Kaolinite is commonly well developed in a humid-tropical climate, particularly in the warm temperate or subtropical regions (Weaver, 1989). Moreover, Konta (1985) included that kaolinite is dominant in tropical rivers. The formation of kaolinite in temperate regions is highly controlled by rainfall and relief. In a humid-tropical climate kaolinite tends to develop in the lowlands and gibbsite in the highlands. In high rainfall areas (e.g. Japan and northern United States) kaolinite and halloysite are the dominant clay minerals (Weaver, 1989). The formation of kaolinite in humid and subtropical regions is similar to the conditions during the deposition of the Meluhu Formation which occurred in meandering river to coastal environments in a subtropical region at a latitude of about 20°S, and probably in wet conditions since the coal macerals are dominated by vitrinite (Surono, 1994b).

DIAGENESIS

A diagenetic study of the Meluhu Formation was carried out by using conventional petrography of thin sections and XRD techniques. Some significant diagenetic features were determined in this study, including compaction, cementation and dissolution.

Compaction

Compaction effects in the Meluhu Formation sandstone are recorded by mica flakes and grain contacts. Mica flakes are bent and some of them are broken. The high amount of bending and breaking of mica flakes in the sandstone indicates that the Meluhu Formation is highly compacted. Fractured plagioclase fragments also occur in many thin sections. Some of the fractures were filled by secondary calcite cement. Ductile lithic fragments can be also observed in some samples, especially from the northeastern area. Some quartz fragments are strained and fractured suggesting deep burial, but they could also have been reworked from older rock units. Three types of fragment contacts (classification of Taylor, 1950) found in most of the samples are long, concavo-convex and sutured. Concavo-convex and sutured contacts are abundant in all samples. Increasing burial depth tends to increase long and concavo-convex contacts and tends to reduce floating and tangential contacts (Taylor, 1950). Sutured contacts will appear at greater burial depth as a result of pressure solution (Boggs, 1992).

Cementation

There are three kind of cements in the Meluhu Formation: silica, carbonate and iron oxide cements. Silica cement is a primary cement, whereas carbonate and iron oxide are generally secondary cements.

Primary calcite cement occurs in a few samples from the Laonti Peninsula. Secondary calcite cement, which is the most common carbonate cement, is also mainly confined to the Laonti Peninsula and has filled fractures and replaced previous cements. Calcite has also replaced some rock fragments, plagioclase and quartz grains along their fractures. Phantom textures of void-filling were determined in one sample from the Laonti Peninsula.

Caries texture, with remaining sutured grain contacts floating in an iron oxide cement, indicates that secondary iron oxide cementation took place after compaction. Iron-rich liquid was probably derived from volcanic rocks and/or from local surface water. The formation of the iron oxide cement probably occurred during the latest stage of diagenesis. This is indicated by the lack of subsequent fractures in the samples.

The combined effects of compaction, cementation and pressure solution in the Meluhu Formation sandstone have resulted in a very tight, interlocking mosaic which is grain-supported and has a very low porosity. These effects reflect the deep burial of the formation.

CONCLUSIONS

The source area of the Meluhu Formation was dominantly occupied by a basement of metamorphic rocks. The metamorphic rocks were probably covered by sedimentary and volcanic rocks. The small percentage of volcanic fragments in the formation suggests that the volcanic rocks formed a thin layer or were of limited lateral extent.

Felsic igneous rock fragments are also a minor component indicating that the igneous rocks probably occurred as dykes and/or sills that intruded the metamorphic rocks, as observed along the Ranteangin River on eastern coast of the Bone Gulf (Surono, 1986).

The mean content of rock fragments in the Meluhu Formation sandstone is 11.3% and the maximum content of 32.4% is in a sample from the northern part. The mixture of weathered and fresh oligoclase fragments in some samples indicates that the relief of the source area was probably rugged. Thick cyclic channel deposits, which coarsen upward, are present in the headwaters of the Andomowu River, south of Tinobu. Grain size at this location varies between a few centimetres up to 35 cm. This sequence was deposited close to the source area and was influenced by reactive vertical tectonism in the source which area formed alluvial fans along the basin margin. A conclusion can be made that the source area for the Meluhu Formation probably had a high relief and likely had high rainfall.

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