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Evolution of the Philippine and Japan Seas from the clastic sediment record

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ABSTRACT

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Mineralogical analyses of the heavy coarse silt fraction, including microprobe identifications of certain clastic minerals, and bulk chemical analyses of 186 sediment samples from DSDP sites 291, 299, 301, 436, 447, 449, 450, 453, 459 and 460 are compared with similar data for Quaternary sediments on a profile across the Pacific from Central America to the Far East. As a result, new details of the history of the Philippine and Japan Seas suggest that the active marginal complex has a variety of "states" (stages). These states differ in terms of (1) the number of associated "echelons" (i.e. parts of the complex), each consisting of a subduction zone, island arc and back-arc basin situated one behind the other, and (2) their orientations. Changes in state are caused by blocking, i.e. hindering, the subduction. Continental as well as oceanic lithosphere is involved in the system. The "island arc" lithosphere, which is more simatic than continental lithosphere and more sialic than oceanic lithosphere, is a final product of the development of the marginal complex irrespective of whether the parent was continental or oceanic lithosphere.

Introduction

The geological development of marginal seas has for a long time been the subject of intense study. These seas result from the activity of subduction zone–island arc–back-arc spreading basin complexes, which includes the entrapment of remnants of the sea and blocks of adjacent plates (Uyeda and Ben-Avracham, 1972; Karig, 1975). For certain seas, in particular the Philippine Sea which is considered here, a general sequence of geodynamic events has been defined (Karig, 1975; Hussong and Uyeda, 1981). However, it is still not clear what caused the structural complications and reversals (reorientations) in the marginal systems, although collisions and plate migration direction change have been hypothetically proposed (Karig, 1974).

The aim of the present paper is to test these propositions by interpreting the geological record in 186 samples of Cenozoic sediments from the Philippine and Japan Seas. This investigation comprises a continuation of a study of Quaternary sediments throughout the North Pacific by Nechaev (1987) and Nechaev and Derkachev (1989). Their study was based on about 800 mineralogical and 600 chemical analyses, including some from the literature; the results from these two articles are briefly described here because they have not been published in English.

Data, methods of analysis and interpretation

Only original data from the DSDP samples are given in the tables below (other data are presented in Figs.1–5).

Percentages of major-element oxides were obtained by wet chemical methods in natural sediments after drying the samples at temperatures below 100°C and then grinding with an agate pestle (Table 1).

Chemical analyses of sediment samples were made by using the interrelationships TiO_2/Al_2O_3 and $(Fe_2O_3{*}+MgO)/Al_2O_3$ (all Fe is given as Fe_2O_3). Unlike others, these characteristics seem

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TABLE 1

Chemical composition (%) of sediments from Deep-Sea Drilling Project samples

Core section /interval (cm)	Sediment	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
Philippine Sea, West Philippine Basin													
Leg 31, Site 291													
2-1/124–131	clay	51.04	0.72	17.68	9.88	–	0.49	3.54	1.71	3.22	2.17	0.18	9.24
2-2/49–56	calc. ooze	16.84	0.21	4.03	2.47	–	0.35	1.90	35.48	2.17	1.05	0.13	34.04
4-2/92–99	clay	55.62	0.15	3.77	13.22	–	2.80	3.60	2.89	4.13	1.33	0.26	10.96
4-4/106–113	clay	52.08	0.15	2.99	16.99	–	2.80	5.37	1.35	3.75	1.86	0.24	12.24
Site 291A													
1-6/84–91	clay	11.72	0.31	1.69	41.32	0.47	15.75	8.91	3.69	2.92	0.80	0.4	12.94
Leg 59, Site 447A													
1-1/30–40	clay	49.06	0.72	18.36	9.28	–	0.70	3.34	1.99	3.70	2.50	+	9.16
1-4/55–62	clay	47.70	1.04	14.24	8.78	–	1.58	3.50	2.22	4.64	2.83	+	12.10
3-2/133–140	clay	48.14	0.72	12.74	14.90	–	0.49	2.86	2.67	3.60	2.25	0.06	7.60
4-1/32–39	clay	51.42	0.31	16.99	8.35	–	1.05	3.02	1.77	3.70	3.89	+	8.60
4-4/80–87	clay	50.48	0.62	15.48	8.82	–	1.23	2.94	3.54	4.89	2.42	+	7.96
5-1/101–108	clay	43.64	0.52	11.51	7.97	–	0.63	3.42	9.72	5.13	2.67	+	16.00
5-6/60–67*	clay	45.66	0.60	11.32	7.79	–	0.33	3.86	7.49	1.96	2.08	0.16	18.04
6-4/50–57	breccia	52.26	0.72	12.19	7.39	–	0.21	3.54	4.20	4.56	2.75	+	11.04
7-1/46–53	breccia	52.98	0.62	12.88	8.75	0.65	0.21	4.13	5.08	3.80	2.00	0.11	7.95
7-6/57–64	breccia	52.70	0.62	14.39	7.05	0.94	0.21	3.66	5.53	4.11	2.17	0.11	7.88
8-6/80–87	breccia	50.74	0.72	14.11	7.84	0.68	0.63	3.90	5.08	4.11	2.50	+	8.37
9-2/124–130	breccia	53.74	0.72	14.52	7.19	1.15	0.07	4.93	3.76	3.30	2.58	+	7.17
10-1/78–81	tuff	51.64	0.62	14.80	10.25	0.55	0.35	3.18	2.44	2.91	4.27	+	7.56
10-2/95–99	breccia	52.50	0.93	16.44	6.04	1.01	0.11	3.10	2.43	4.44	4.82	+	7.73
12-1/110–117	breccia	45.86	0.93	18.36	6.83	3.28	0.21	5.88	11.60	2.25	0.35	0.66	3.52
12-2/67–70	breccia	44.02	0.93	16.30	7.65	1.12	0.11	6.68	5.86	2.83	3.22	+	9.76
13-1/45–50*	breccia	41.92	0.95	14.20	7.70	1.64	0.15	4.75	10.07	2.40	2.50	0.16	12.97
Parece Vela Basin													
Site 449													
2-1/92–99	clay	48.00	1.04	16.98	8.70	–	0.70	3.40	2.46	4.33	2.67	+	10.70
2-3/52–59	clay	48.26	0.72	17.26	9.86	–	0.70	3.58	2.32	4.00	2.50	+	11.52
3-1/55–62	clay	47.22	0.72	16.03	10.32	–	1.40	3.66	2.65	4.00	2.58	+	11.90
3-4/80–87	clay	47.16	0.72	17.26	10.20	–	1.23	4.29	1.99	3.90	1.75	+	10.96
4-3/94–101	clay	50.00	0.52	16.30	8.93	–	0.49	4.69	2.54	4.25	1.75	+	10.46
5-3/70–77	clay	50.38	0.52	14.52	8.66	–	0.63	4.85	3.09	4.63	1.38	+	11.32
6-2/139–143	ash	63.96	0.42	11.78	3.38	0.85	0.21	0.80	2.22	4.00	3.78	+	8.37
6-4/70–77	calc. ooze	18.16	0.31	5.21	4.50	–	0.70	0.80	34.59	2.58	1.19	+	31.68
7-1/52–59*	clay	50.35	0.57	13.40	10.09	–	1.06	4.25	3.46	1.53	0.97	0.46	13.36
7-4/52–59	calc. ooze	34.02	0.62	9.04	3.46	0.49	0.42	1.60	20.12	4.13	0.96	+	+
7-5/96–103*	clay	52.79	0.57	10.90	8.67	1.26	0.54	4.32	5.35	1.33	0.59	0.29	12.73
8-3/40–47*	clay	46.90	0.60	11.36	12.99	–	0.96	4.42	3.81	1.63	0.86	0.32	16.00
10-3/90–97	clay	46.76	0.49	11.81	12.04	–	0.76	3.94	2.01	1.84	1.71	0.25	18.34
11-1/70–77*	clay	42.07	0.54	10.99	9.89	–	0.82	3.88	7.29	1.42	1.89	0.30	20.24
12-1/53–60	calc. ooze	31.08	0.62	8.76	10.24	–	1.75	1.91	17.68	4.09	1.94	+	21.99
12-3/20–27	calc. ooze	15.35	0.23	3.76	4.35	–	0.89	2.01	36.86	0.77	0.59	0.27	34.60
13-1/80–87	calc. ooze	14.70	0.31	9.18	8.47	–	2.45	2.30	31.71	2.58	1.25	+	26.74
13-5/40–47	calc. ooze	16.16	0.31	4.66	5.51	–	1.23	0.71	35.69	1.19	0.70	+	34.36
13-6/102–109	calc. ooze	10.72	0.24	3.84	3.70	–	1.05	2.06	44.28	1.38	0.50	+	32.36
Site 450													
1-1/90–97	clay	49.84	0.62	16.72	8.34	1.03	0.70	4.30	5.08	4.36	2.00	+	7.31
2-4/80–87	clay	47.22	0.72	20.69	10.66	–	1.05	3.25	3.69	3.88	2.00	0.35	6.44
3-6/88–95	clay	50.04	0.52	17.54	9.36	–	0.56	3.25	3.76	4.00	2.08	0.31	7.21
4-1/110–117	clay	54.66	0.52	15.76	5.34	2.61	0.21	2.39	6.41	3.75	1.63	0.11	4.76

TABLE 1 (*continued*)

Core section /interval (cm)	Sediment	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
5-4/38–45	clay	55.76	0.52	15.76	5.92	2.30	0.21	2.39	5.97	3.63	1.38	0.06	4.36
6-1/24–31	clay	52.32	0.52	13.56	4.40	2.39	0.21	2.07	9.64	3.50	1.56	0.06	8.78
8-1/21–28	clay	63.20	0.41	13.56	2.47	1.56	0.21	1.35	3.20	4.00	2.42	0.03	6.01
12-1/64–67	tuff	54.58	0.73	14.38	5.93	2.98	0.07	2.84	6.16	3.67	1.75	0.11	6.73
14-3/96–100	tuff	54.56	0.73	14.52	6.16	2.91	0.21	3.40	6.16	3.33	1.50	0.11	6.82
14-5/69–72	tuff	55.60	0.73	14.95	4.93	3.90	0.07	2.67	6.27	3.40	1.60	0.06	4.93
17-4/41–44	tuff	54.54	0.73	14.81	5.22	2.72	0.21	2.61	7.15	3.33	1.50	0.11	6.90
19-2/122–125	tuff	54.00	0.73	13.96	5.42	2.82	0.10	2.77	6.82	3.33	1.50	0.07	7.91
24-2/80–87	tuff	55.24	0.73	15.23	3.90	3.91	0.21	2.69	7.15	3.33	1.50	0.07	5.93
29-2/72–75	tuff	59.00	0.52	12.97	2.32	2.14	0.21	1.66	6.27	3.33	2.00	0.07	8.64
34-1/136–139	tuff	57.60	0.62	13.82	4.89	2.36	0.21	3.16	4.62	3.33	1.50	0.11	7.46
35-2/18–21	tuff	59.16	0.41	12.88	4.06	1.82	0.21	2.46	5.41	3.00	1.19	+	7.80
36-2/107–110	tuff	52.30	0.73	16.64	10.36	–	0.49	3.71	1.76	3.00	4.00	+	7.10
Mariana Trough													
Leg 60, Site 453													
1-1/106–113	mud	55.34	0.52	13.11	6.46	2.02	0.07	2.77	3.63	5.00	1.75	+	9.22
3-1/78–85	mud	50.50	0.73	15.51	8.39	2.15	0.49	3.32	5.94	4.50	1.50	0.15	7.24
4-4/40–47	mud	50.94	0.62	13.88	8.96	1.32	0.21	2.69	3.30	5.50	2.00	0.15	9.47
6-1/80–87	mud	48.86	0.73	16.92	9.03	1.58	0.21	4.11	5.94	+	+	0.11	+
8-3/71–78	clay	46.42	0.73	12.97	12.87	1.17	0.21	4.19	2.75	5.50	2.50	+	10.63
12-5/70–77	mud	43.80	0.62	11.00	21.51	2.75	0.35	3.16	4.40	3.33	1.25	0.15	7.50
13-1/52–59	claystone	48.40	0.73	14.38	9.66	1.32	0.21	4.03	3.74	5.00	2.00	0.11	9.75
14-1/54–61	claystone	49.68	0.73	15.22	7.65	2.54	0.35	3.56	5.17	+	+	0.15	9.18
15-3/8–15	claystone	47.92	0.67	14.66	9.62	0.84	0.21	4.82	3.74	4.50	2.25	0.24	9.79
18-3/53–59	claystone	47.10	0.67	13.40	9.89	1.22	0.35	6.56	2.09	+	+	0.24	10.53
20-1/94–101	mudstone	49.34	0.62	13.40	11.82	0.88	0.13	4.90	2.42	4.00	2.75	+	9.60
21-1/53–60	mudstone	53.58	0.42	14.95	10.52	0.65	0.10	2.45	2.09	4.00	1.75	0.15	9.67
24-2/76–83	mudstone	60.90	0.52	13.11	2.51	2.65	0.21	1.58	3.74	4.00	2.50	0.02	9.39
26-2/74–81	mudstone	58.96	0.52	12.69	2.88	2.54	0.21	1.98	4.29	4.00	2.25	0.11	9.78
29-1/103–110	mudstone	54.98	0.67	14.38	6.52	2.80	0.07	3.79	3.74	3.67	2.00	0.07	6.31
31-1/80–87	mudstone	57.90	0.58	12.97	4.38	2.30	0.07	2.21	4.73	3.67	1.75	0.07	9.05
34-2/95–102	mudstone	51.34	0.73	14.38	8.74	1.43	0.10	3.63	5.06	3.00	1.50	0.57	8.55
37-4/65–72	mudstone	53.40	0.73	14.38	8.24	1.22	0.21	3.95	3.52	3.67	2.00	0.15	7.53
41-4/143–150	mudstone	56.40	0.62	12.69	5.66	2.74	0.21	4.42	4.73	3.40	1.25	0.15	6.80
45-3/29–32	sandstone	56.34	0.67	15.23	6.51	2.95	0.04	4.84	4.73	2.67	1.00	0.07	5.42
48-1/28–31	sandstone	49.60	0.83	16.92	9.74	1.43	0.04	8.53	0.44	1.75	3.50	0.06	6.90
Mariana Arc													
Site 459B													
1-1/73–80	ash	47.14	0.58	13.95	3.88	2.35	0.19	2.44	13.46	3.86	1.25	0.21	10.23
2-4/40–44	ash	50.45	0.82	13.77	7.05	2.35	0.33	4.62	5.18	3.83	1.44	0.39	9.19
5-1/15–19	ash	52.86	0.98	13.62	5.91	5.07	0.19	3.52	6.57	3.77	1.29	0.43	5.25
6-1/64–71	ash	50.90	0.69	15.12	7.16	0.57	0.30	4.20	3.47	3.72	1.29	0.35	11.78
6-4/27–32	ash	54.22	0.68	15.08	5.78	1.69	0.17	2.78	4.57	4.31	2.06	0.38	8.09
8-1/42–48	ash	54.30	0.66	15.09	6.23	2.43	0.15	3.04	5.47	3.74	1.56	0.33	6.72
11-1/38–45	tuff	54.65	0.63	14.86	4.21	1.74	0.13	1.88	3.86	2.74	2.21	0.22	12.29
15-1/64–71	tuff	53.58	0.74	14.27	6.16	2.38	0.18	4.38	5.40	3.74	1.48	0.26	6.96
17-1/70–77	tuff	54.90	0.66	13.55	5.07	2.58	0.16	4.01	5.30	4.05	1.59	0.32	7.35
21-1/40–47	tuff	45.30	0.45	11.78	2.39	2.87	0.25	1.80	16.30	3.65	0.97	0.26	13.96
25-1/42–49	tuff	57.17	0.77	14.43	5.08	2.75	0.17	2.49	6.25	3.87	0.99	0.23	5.40
27-3/23–30	tuff	56.10	0.86	13.82	4.67	4.29	0.16	3.10	6.14	3.86	1.01	0.23	5.70
30-3/73–80	tuff	54.14	0.82	13.48	5.64	4.30	0.21	3.85	6.59	3.78	0.99	0.30	5.42
34-1/39–46	tuff	61.80	0.63	13.06	3.27	2.75	0.15	1.68	4.11	4.28	0.94	0.26	7.14
37-1/103–107	tuff	57.52	0.68	14.66	3.43	3.68	0.21	2.31	7.14	4.05	0.71	0.26	4.86

TABLE 1 (*continued*)

Core section /interval (cm)	Sediment	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
39-2/95–99	tuff	63.08	0.54	13.39	2.47	3.45	0.17	0.99	4.25	4.17	0.84	0.24	6.46
42-2/0–7	tuff	56.45	0.85	14.86	3.66	4.62	0.21	2.83	7.04	3.51	0.71	0.24	4.86
46-2/47–54	tuff	51.40	0.51	12.05	4.37	2.45	0.17	2.21	11.78	3.26	0.68	0.30	10.34
47-1/113–120	tuff	46.10	0.52	9.97	3.54	2.51	0.19	2.07	15.90	2.86	0.76	0.28	14.88
50-1/0–7	tuff	54.90	0.63	15.18	4.94	3.24	0.14	3.89	7.05	3.12	0.86	0.28	5.26
52-1/50–57	tuff	64.80	0.43	11.04	2.25	1.81	0.20	1.20	3.24	4.85	1.21	0.22	8.24
53-2/4–11	tuff	48.56	0.68	11.22	3.75	3.12	0.17	2.71	12.25	2.69	0.79	0.25	13.25
54-4/23–26	sandstone	39.59	0.42	9.56	1.68	3.83	0.39	1.94	22.36	2.23	0.45	0.24	16.75
51-1/91–98	claystone	54.12	0.57	14.08	7.36	0.68	0.13	3.37	2.79	2.50	2.22	0.33	11.43
56-4/60–67	claystone	51.84	0.57	14.31	9.04	–	1.20	2.83	2.57	2.82	2.24	0.54	12.07
58-2/107–114	tuff	53.12	0.65	12.60	8.22	–	0.44	3.66	3.34	2.81	0.93	0.32	13.69
59-1/177–124	claystone	66.20	0.34	7.97	3.65	0.72	0.23	3.39	2.77	2.69	1.04	0.09	10.60
60-1/8–15	claystone	52.15	0.55	14.88	8.84	–	0.94	3.47	1.82	2.87	3.11	0.15	10.99
Inner slope of Mariana Trench													
Site 460													
1-1/72–79	mud	53.73	0.94	11.07	5.88	1.81	0.32	6.29	2.92	3.63	1.92	0.27	10.62
1-5/40–47	mud	62.86	0.57	8.08	3.61	1.38	0.26	3.39	2.64	4.35	1.36	0.25	10.82
3-1/53–60	mud	47.53	0.85	12.55	8.61	1.26	0.37	8.05	3.60	3.60	1.48	0.24	11.46
3-5/37–44	mud	49.56	1.08	11.63	7.54	1.37	0.13	9.22	2.62	3.24	1.75	0.14	11.23
4-1/90–97	mud	42.57	0.75	9.75	15.68	2.49	0.41	8.73	3.01	2.66	1.21	0.31	11.96
4-3/30–37	mud	47.38	1.08	10.72	8.33	1.33	0.18	9.87	2.77	3.37	1.88	0.34	12.38
4-6/5–12	mud	48.70	1.01	14.53	9.52	–	0.48	3.61	2.93	3.86	1.29	0.26	13.27
5-1/30–37	tuff	50.80	0.68	13.65	9.28	1.68	0.24	4.47	4.25	3.03	1.28	0.13	9.88
6-1/80–87	tuff	53.48	0.65	13.43	7.33	1.71	0.17	4.39	3.89	3.34	1.36	0.14	9.42
6-2/20–27	tuff	57.98	0.51	10.51	7.64	1.39	0.47	3.61	2.93	2.82	0.90	0.23	10.48
7-1/79–86	tuff	52.60	0.49	11.89	6.87	–	0.72	5.92	1.82	2.69	1.86	0.32	14.10
8-1/37–44	tuff	48.15	0.54	14.20	8.04	1.42	0.32	4.47	5.55	3.45	2.61	0.09	11.04
Japan Sea													
Leg 31, Site 299													
1-1/101–110	clay	54.54	0.52	15.34	4.48	1.51	0.25	2.31	1.58	3.88	2.89	0.11	12.36
2-5/97–104	clay	56.82	0.62	16.25	3.01	1.70	0.14	2.04	1.73	3.25	2.78	0.11	11.38
3-3/91–95	ash	57.42	0.52	15.08	3.37	2.10	0.11	0.88	1.28	4.75	5.00	0.08	8.81
5-1/80–87	clay	49.82	0.62	14.30	3.58	1.64	0.11	2.18	5.06	2.86	2.83	0.11	15.96
7-2/104–108	ash	68.06	0.41	11.18	1.03	1.40	0.11	0.34	2.57	3.57	2.44	0.04	8.44
8-3/80–87	clay	61.94	0.52	13.52	2.56	1.08	0.11	1.43	2.47	2.93	3.27	0.07	9.61
9-5/70–74	sand	61.54	0.52	14.43	2.05	1.23	0.11	0.95	4.56	3.14	2.67	0.09	8.19
11-6/58–65	clay	52.20	0.52	11.96	2.37	1.19	0.49	1.43	9.31	2.79	2.22	0.24	14.44
12-3/20–24	ash	66.80	0.31	12.74	1.07	1.13	0.06	0.68	1.62	3.00	4.00	0.04	8.17
12-4/48–52	sand	62.70	0.52	13.91	1.89	1.51	0.11	0.68	4.47	2.86	2.44	0.07	8.13
14-5/16–20	sand	64.88	0.52	14.04	2.13	1.43	0.11	0.95	3.23	3.00	2.61	0.08	6.20
16-1/106–110	sand	68.40	0.52	12.48	1.90	1.50	0.06	0.88	2.38	3.43	2.61	0.08	5.31
17-3/78–82	sand	72.52	0.41	11.44	0.76	1.54	0.06	0.75	2.28	3.43	2.56	0.06	4.42
19-1/86–90	sand	63.74	0.52	14.30	3.12	0.99	0.11	0.88	1.71	3.14	3.00	0.06	9.04
20-2/126–130	sand	67.40	0.72	14.04	2.16	1.34	0.06	1.02	2.57	2.77	2.61	0.09	5.96
22-2/80–87	clay	60.62	0.52	14.17	2.73	1.38	0.11	1.50	2.09	3.00	2.78	0.08	9.21
24-2/110–117	claystone	61.18	0.52	13.52	3.41	1.07	0.11	1.02	2.09	2.85	2.61	0.07	10.05
28-1/126–130	sand	67.00	0.52	14.17	2.36	1.37	0.11	1.16	2.00	2.92	2.83	0.07	5.86
29-1/134–138	sand	62.74	0.52	12.35	3.01	1.53	0.06	1.63	1.71	4.00	2.50	0.06	10.21
30-3/46–53	claystone	59.88	0.52	14.69	4.60	1.23	0.28	1.77	2.00	2.62	2.67	0.05	9.22
31-2/25–32	claystone	57.62	0.72	14.56	3.49	1.38	0.14	1.90	1.71	2.54	2.56	0.05	13.16
32-2/72–79	claystone	58.08	0.62	15.21	3.79	1.96	0.11	2.18	1.95	2.50	2.72	0.08	10.32
33-2/57–64	claystone	60.22	0.72	16.25	3.36	2.18	0.11	2.52	1.71	2.46	2.56	0.07	7.60
35-1/76–80	sand	69.88	0.21	11.31	1.05	1.04	0.07	0.75	1.20	3.50	3.55	0.04	7.72

TABLE 1 (*continued*)

Core section /interval (cm)	Sediment	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
36-4/88–95	claystone	60.06	0.62	15.08	3.47	1.63	0.07	2.24	1.20	2.50	2.61	0.08	10.12
37-3/60–67	claystone	56.40	0.62	15.08	3.88	2.19	0.18	2.31	1.91	2.33	2.50	0.06	11.94
38-4/53–60	sand	49.18	0.72	14.43	6.09	3.24	0.25	2.65	9.23	3.00	1.82	0.06	8.52
38-5/107–111	sand	65.80	0.62	13.78	2.26	1.80	0.11	1.36	1.95	2.75	2.67	0.06	5.98
Site 301													
2-4/105–110	ash	56.98	0.62	14.82	2.76	2.06	0.11	1.70	1.24	3.86	3.00	0.11	12.66
4-4/96–100	ash	66.02	0.31	11.57	2.16	1.21	0.25	0.14	1.24	3.71	4.45	0.04	8.74
4-5/56–60	sand	68.22	0.72	13.26	2.90	1.36	0.07	0.88	2.28	3.00	2.56	0.13	4.03
9-1/113–119	clay	59.68	0.72	14.82	3.73	1.33	0.11	1.90	1.24	2.43	2.72	0.04	10.82
15-4/130–134	silt	68.46	0.52	12.48	3.42	0.78	0.06	0.68	1.05	2.69	2.67	0.04	6.81
17-1/80–84	sand	66.70	0.52	12.61	3.37	0.73	0.07	0.41	2.85	2.77	2.83	0.06	6.45
18-4/6–10	sand	64.20	0.52	13.00	3.59	1.08	0.14	0.61	2.00	3.00	2.78	0.06	8.59
20-3/63–70	clay	60.74	0.72	14.95	3.87	1.23	0.11	1.36	1.43	2.76	2.86	0.04	9.59
Outer slope of Japan Trench													
Leg 56, Site 436													
1-4/80–87	clay	60.90	0.52	12.74	4.34	2.08	0.11	1.84	2.28	3.88	2.28	0.06	8.78
4-1/92–99	clay	64.20	0.52	12.61	2.94	1.46	0.06	1.16	1.90	4.00	2.22	0.06	8.10
6-3/90–97	clay	62.82	0.52	13.39	2.41	1.90	0.11	1.43	2.19	4.00	2.39	0.06	8.56
8-3/78–85	clay	60.66	0.72	13.78	3.80	1.37	0.07	1.90	1.90	4.13	2.56	0.06	8.62
10-1/77–84	clay	59.00	0.41	11.05	2.52	1.46	0.11	0.75	2.76	4.00	1.82	0.04	15.57
11-4/30–37	clay	62.58	0.52	13.52	3.52	1.52	0.06	1.22	2.57	3.88	2.11	0.04	8.30
12-4/50–57	clay	67.40	0.31	11.96	1.81	1.07	0.07	0.68	1.43	3.88	3.09	0.04	8.22
14-3/118–125	clay	65.02	0.52	11.70	2.12	1.51	0.07	1.36	2.00	4.00	2.00	0.04	9.47
15-6/13–20	clay	66.64	0.41	12.09	1.17	1.55	0.11	0.95	1.71	3.63	2.67	0.04	8.08
17-3/80–87	clay	66.44	0.41	12.35	2.82	1.57	0.11	0.68	2.47	3.88	1.91	0.04	7.20
18-1/69–76	clay	63.42	0.52	10.79	4.71	1.65	0.11	0.82	2.19	3.78	2.16	0.04	8.84
20-1/69–76	clay	64.46	0.41	12.87	1.90	1.33	0.06	0.82	2.09	1.87	2.86	0.04	9.00
22-1/66–73	clay	64.46	0.52	12.74	2.70	1.26	0.06	1.29	1.50	3.44	2.63	0.04	8.80
23-2/74–81	clay	64.02	0.52	12.61	3.21	1.22	0.06	1.02	1.50	3.44	2.58	0.04	9.72
25-1/37–44	clay	60.80	0.72	13.78	3.79	1.79	0.06	1.43	1.91	3.33	2.32	0.04	9.70
27-1/117–124	clay	62.38	0.52	13.39	3.70	1.15	0.06	1.50	1.52	4.16	2.96	0.04	8.09
29-1/54–61	claystone	66.96	0.31	12.74	1.94	1.20	0.07	0.88	1.31	1.87	2.76	0.04	9.40
30-1/94–101	claystone	66.04	0.62	12.06	2.57	0.80	0.07	0.01	2.88	3.60	2.58	+	8.09
31-3/77–84	claystone	61.84	0.62	13.42	4.15	1.18	0.49	0.72	2.44	3.43	2.42	+	8.53
32-2/96–103	claystone	62.76	0.52	13.02	4.15	0.95	0.21	1.91	1.44	2.92	2.58	+	9.90
33-6/88–95	claystone	67.22	0.31	12.88	2.30	0.84	0.11	0.32	1.66	2.46	2.50	+	9.09
34-5/83–90	claystone	61.14	0.52	13.56	4.47	0.83	0.21	1.75	1.55	3.00	2.92	+	9.33
36-4/92–99	claystone	60.40	0.52	16.17	5.37	0.64	0.35	1.83	1.22	3.00	3.00	+	7.27
37-2/113–120	claystone	58.48	0.62	15.62	5.17	0.68	1.58	2.22	1.76	2.54	2.83	+	8.27
38-2/77–84	claystone	61.36	0.52	15.21	4.87	0.26	0.63	1.67	1.55	2.77	3.11	+	6.70
38-6/106–113	claystone	61.44	0.62	13.98	5.21	0.37	0.28	1.12	1.98	2.45	2.50	+	9.74
39-1/106–113	claystone	58.64	0.52	17.13	6.78	–	0.63	3.26	1.22	2.45	2.08	0.15	6.96
39-4/32–39	claystone	56.82	0.93	17.54	6.39	–	0.88	2.46	1.55	2.36	2.92	0.11	6.64
40-2/72–79	claystone	53.46	0.73	19.45	7.16	–	1.54	3.40	0.88	2.00	5.00	0.11	6.20
40-4/63–70	claystone	53.08	0.72	19.32	7.08	–	1.75	3.11	1.77	1.83	4.00	0.26	7.15
40-6/75–82	claystone	53.08	0.62	18.90	6.54	–	1.75	2.86	2.64	1.92	3.22	+	7.10

LOI = loss on ignition.

*0.05 mm fraction (selected by wet sieving) was analyzed because the sample volume was not sufficiently large for both chemical and mineralogical analyses. As a result of sieving, the seawater salts were washed out of the samples. In other cases natural sediments were analyzed.

Dashes = not found; plus signs = not determined.

TABLE 2

Percentage of heavy clastic minerals in the 0.05–0.1 mm fraction of the sediment samples from Deep-Sea Drilling Project cores

Core section/ interval (cm)		Clino- pyroxene		Ortho- pyroxene		Amphibole																
	Ol	Cpx_1	Cpx_2	Opx_1	Opx_2	Hb	Am	Ep	Grn	Cor	Per	Zr	Trm	Bi	Ap	Rut	Sph	Lcx	Mt	Ilm	Cr	No.
Philippine Sea, West Philippine Basin																						
Leg 31, Site 291																						
2-1/124–131	–	0.7	57	–	1.3	3.4	–	4	–	–	–	–	–	0.7	5.4	–	–	–	24.2	2	1.3	149
2-2/49–56	–	–	42	–	10.5	10.5	–	5.3	–	–	5.3	–	–	10.5	–	–	–	–	10.5	5.3	–	19
4-2/92–99	–	–	27.6	–	7.9	5.3	–	3.9	–	–	–	–	–	1.3	–	–	–	–	52.6	1.3	–	76
4-4/106–113	–	–	15.7	–	2.9	5.9	–	1	–	–	–	–	–	2.9	–	–	–	–	62.8	8.8	–	102
Site 291A																						
1-6/84–91	–	–	61.2	–	10.6	–	1.2	4.7	1.2	8.2	1.2	–	–	7.1	1.2	–	–	–	3.5	–	–	84
Leg 59, Site 447A																						
1-1/30–40	0.7	–	4.2	–	–	5.6	–	2.8	–	–	–	–	–	–	–	–	–	–	80.3	6.3	–	142
1-4/55–62	–	–	2.2	–	0.7	1.5	–	0.4	–	–	–	–	–	–	–	–	–	0.4	94.4	0.4	–	269
3-2/133–140	–	–	4.5	–	0.5	–	–	0.9	–	–	–	–	–	2.3	0.9	–	–	–	90.5	0.5	–	221
4-1/32–39	–	–	25.1	–	1	2	–	1	0.5	–	–	0.5	–	–	1	–	–	–	68.3	0.5	–	199
4-4/80–87	–	–	13.8	–	0.3	3.6	–	11.1	–	–	–	–	–	–	0.3	–	0.3	–	68.9	1.8	–	334
5-1/101–108	4.6	–	27.3	–	4.6	–	4.6	4.6	–	–	–	–	–	–	–	–	–	–	52.3	2.3	–	44
5-6/60–67	–	–	12	–	3.4	3.8	–	7	–	–	–	2	–	–	–	–	–	1	5	1	–	100
6-4/50–57	–	–	44.3	–	0.8	2.1	–	1.2	–	–	–	–	–	–	–	–	–	–	43.4	8.2	–	244
7-1/46–53	0.4	–	57.8	–	10.1	9.8	–	0.8	–	–	–	0.4	–	–	0.4	–	–	–	19.8	0.4	–	237
7-6/57–64	–	0.9	56.3	–	2.3	5.2	–	14.3	–	–	–	–	–	–	0.9	–	–	–	19	1.3	–	231
8-6/80–87	–	–	48.5	–	7.6	3	–	1	–	–	–	–	–	–	–	–	–	–	33.3	6.6	–	198
9-2/124–130	–	–	59	–	–	7.6	–	2.2	–	–	–	–	–	–	0.3	–	–	–	26.9	3.9	–	364
10-1/78–81	1.4	–	9.3	–	2.3	0.9	–	2.3	–	–	–	–	–	–	0.9	–	–	–	81.8	0.9	–	214
10-2/95–99	2.8	4.6	47.5	–	3.2	5.5	–	1.4	–	–	–	–	–	–	0.5	–	–	–	31.3	2.3	0.9	217
12-2/67–70	84	1.5	9.7	–	–	0.5	–	0.5	–	–	–	–	–	–	0.5	–	–	–	1	0.5	1.9	207
13-1/49–50	45.5	8.4	42.6	–	1	–	–	–	–	–	–	–	–	–	0.5	–	–	–	0.5	0.5	1	202
Parece Vela Basin																						
Leg 59, Site 449																						
2-1/92–99	–	–	40.7	–	6.2	4.8	–	2.8	–	–	–	–	–	–	–	–	–	–	44.1	1.4	–	145
2-3/52–59	–	–	22.5	–	8	1.4	–	1.4	–	–	–	–	–	–	–	–	0.7	–	65.2	0.7	–	138
3-1/55–62	–	–	38.8	–	4.8	1.2	–	–	–	–	–	–	–	–	0.4	–	–	–	53.2	1.6	–	250
3-4/80–87	–	–	16.8	–	–	14.1	–	2.3	–	–	–	–	–	–	0.4	–	–	–	66.4	–	–	256
4-3/91–101	–	–	19.5	–	0.4	1.8	–	3.6	–	–	–	–	–	–	–	–	–	–	73.6	1.3	–	231
5-3/70–77	–	–	61.4	–	1.8	3.7	–	2.2	–	–	–	–	–	–	0.4	–	–	–	30.1	0.4	–	272
6-2/139–143	–	–	0.5	–	48.8	–	–	–	0.5	–	–	0.5	–	0.5	0.5	–	–	–	1.5	47.3	–	205
6-4/70–77	–	–	49.8	–	18.2	0.8	–	1.2	–	–	–	–	–	–	0.4	–	–	–	25.1	4.5	–	247
7-1/57–59	–	–	18.3	–	17.3	–	–	0.5	–	–	–	–	–	–	0.5	–	–	–	62.5	1	–	208
7-4/52–58	–	–	58.8	–	24.2	3.3	–	2.8	–	–	–	0.5	–	–	–	–	0.5	0.5	7.7	1.7	–	182

7-5/96–103	–	–	59.3	–	31.5	0.9	–	2.8	–	–	–	–	–	–	–	–	–	–	5.1	0.5	–	216
8-3/40–47	–	–	49	–	9.6	6.7	–	1.6	–	–	–	–	–	–	0.3	–	–	–	32.5	0.3	–	314
10-3/90–97	–	–	10.8	–	0.5	12.6	–	0.9	–	–	–	–	–	–	0.5	–	–	–	73.1	1.8	–	223
11-1/70–77	–	–	12.1	–	0.5	1	–	1.9	–	–	–	–	–	–	0.5	–	–	–	82	1.9	–	206
12-1/53–60	–	–	7.7	–	0.5	0.5	–	3.6	–	–	–	–	–	–	–	–	–	–	87.2	0.5	–	195
12-3/20–27	–	–	9.8	–	1.3	2.1	–	5.1	–	–	–	–	–	–	–	–	–	–	80	1.7	–	235
13-1/80–87	–	–	6.1	–	–	1.8	–	0.4	–	–	–	–	–	–	–	–	–	–	85.3	6.1	–	228
13-5/40–47	–	–	11.8	–	–	0.5	–	1.9	–	–	–	–	–	–	–	–	–	–	83	2.8	–	212
13-6/102–109	–	–	37.6	–	2.9	10.9	–	2.1	–	–	–	–	–	–	0.4	–	0.4	1.3	42.7	1.3	–	239
Site 450																						
1-1/90–97	–	–	71.5	–	10.2	1.2	–	0.8	–	–	–	–	–	–	–	–	–	–	16.4	–	–	256
2-4/80–87	–	–	69.2	–	1.7	0.4	–	0.4	–	–	–	–	–	–	–	–	–	–	27.4	0.8	–	237
3-6/88–95	–	–	61.9	–	1.3	6.8	–	0.3	–	–	–	–	–	–	0.3	–	–	–	29	0.3	–	307
4-1/110–117	–	–	77.1	–	9.2	1.3	–	0.4	–	–	–	–	–	–	–	–	–	–	11.7	0.4	–	240
5-4/38–45	–	–	81.8	–	9.1	0.8	–	3.3	–	–	–	–	–	–	0.4	–	–	–	4.4	–	–	275
6-1/24–31	–	–	44.3	–	36.7	0.8	–	2.3	–	–	–	–	–	–	0.4	–	–	–	15.1	0.4	–	264
8-1/21–28	–	–	38.8	–	26.7	0.5	–	1	0.5	–	–	–	–	–	0.5	–	–	–	31.6	0.5	–	206
12-1/64–67	–	–	57.2	–	21.9	0.5	–	0.5	–	–	–	–	–	–	–	–	–	–	19.5	0.5	–	215
14-3/76–100	–	–	41	–	33.3	2.0	–	1	–	–	–	–	–	–	–	–	–	–	21	1.5	–	195
14-5/67–72	–	–	66.8	–	13.5	1.0	–	0.5	–	–	–	–	–	–	0.5	–	–	–	17.6	–	–	193
17-4/41–44	–	–	58.3	–	15	–	–	1.1	–	–	–	–	–	–	–	–	–	–	25.6	–	–	180
19-2/122–125	–	–	36.4	–	18.2	1.5	–	1.5	–	–	–	–	–	–	12.1	–	–	–	30.3	–	–	66
24-2/80–87	–	–	70.9	–	7	0.5	–	0.5	–	–	–	–	–	–	0.5	–	–	–	20.2	0.5	–	213
29-2/72–75	–	–	65	–	6.3	–	–	2.5	–	–	–	–	–	–	–	–	–	–	26.3	–	–	80
34-1/136–139	–	–	52.9	–	18.8	0.6	–	2.4	–	–	–	–	–	–	–	–	–	–	25.3	–	–	170
35-2/18–21	1.6	–	26.6	–	15.6	4.7	–	3.1	–	20.3	–	–	–	–	1.6	–	–	–	26.6	–	–	64
36-2/107–110	–	–	1.9	–	–	2.8	–	0.5	–	–	–	–	–	–	0.5	–	–	–	93.9	0.5	–	213
Mariana Trough																						
Leg 60, Site 453																						
1-1/106–113	8	–	63.3	–	13.3	0.4	–	0.4	–	–	–	–	–	–	–	–	–	–	14.6	–	–	226
3-1/78–85	0.5	–	84.1	–	9	–	–	0.5	–	–	–	–	–	–	–	–	–	–	6	–	–	201
4-4/40–47	–	–	65.4	–	14.2	–	0.5	0.5	–	–	–	–	–	–	–	0.5	–	–	19	–	–	211
6-1/80–87	2	–	66	–	22	–	–	0.5	–	–	–	–	–	–	–	–	–	–	9.5	–	–	200
8-3/71–78	–	–	83.1	–	9	2	–	0.5	–	–	–	–	–	–	–	–	–	–	5.5	–	–	201
12-5/70–77	0.9	–	66.2	–	21	–	0.4	0.4	–	–	–	–	–	–	–	–	–	–	11	–	–	228
13-1/52–59	–	–	70.6	–	18.4	–	–	–	–	–	–	–	–	–	–	–	–	–	11	–	–	245
14-1/54–61	–	–	79.4	–	15.7	–	–	–	–	–	–	–	–	–	–	–	–	–	3.9	1	–	102
15-3/8–15	–	–	91.7	–	1	0.5	0.5	0.5	–	–	–	–	–	–	0.5	–	–	–	4.9	0.5	–	205
18-3/53–59	–	–	83.1	–	1	0.5	–	–	–	–	–	–	–	–	–	–	–	–	14.9	0.5	–	201
20-1/94–101	–	–	74.4	–	0.8	–	–	–	–	–	–	–	–	–	–	–	–	–	23.2	1.6	–	125
21-1/53–60	–	–	86	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	12	1	–	100
24-2/76–83	–	–	33.3	–	16.2	–	–	–	–	–	–	–	–	–	5.9*	–	–	–	44.1	0.5	–	204
26-2/74–81	–	–	49.4	–	14.9	–	–	–	–	–	–	–	–	–	–	–	–	–	35.6	–	–	87
29-1/103–110	–	–	69	–	24.5	0.5	–	0.5	–	–	0.5	–	–	–	0.5*	–	–	–	4.5	–	–	200
31-1/80–87	–	–	66.7	–	21.7	–	–	1.7	1.7	–	–	–	–	–	–	–	–	–	8.3	–	–	60
34-2/95–102	–	–	38.5	–	10.6	–	–	–	–	–	–	–	–	–	3.9*	–	–	–	46.2	1	–	104

TABLE 2 (*continued*)

Core section/ interval (cm)		Clino- pyroxene		Ortho- pyroxene		Amphibole																
	Ol	Cpx_1	Cpx_2	Opx_1	Opx_2	Hb	Am	Ep	Grn	Cor	Per	Zr	Trm	Bi	Ap	Rut	Sph	Lcx	Mt	Ilm	Cr	No.
37-4/65-72	–	–	12.4	–	1	–	–	–	–	–	72.2	–	–	–	3.1*	–	–	–	11.3	–	–	97
41-4/143-150	–	–	65.9	–	16.5	–	–	2.4	1.2	–	–	–	–	–	–	–	–	–	14.1	–	–	85
45-3/29-32	–	–	66.5	–	24.5	0.4	–	0.4	–	–	0.4	–	–	–	0.8*	–	–	–	6.5	0.4	–	245
48-1/28-31	–	–	10.4	–	8.9	–	0.5	11.9	0.5	–	–	–	–	–	1*	–	–	–	66.8	–	–	202
Mariana Arc																						
Site 459B																						
1-1/73-80	0.5	–	57.1	–	20.3	0.5	–	0.5	0.5	–	–	–	–	–	–	–	–	–	20.3	0.5	–	217
2-4/40-44	4.9	–	77.2	–	13.6	1	–	0.5	–	–	–	–	–	–	–	–	–	–	2.4	0.5	–	206
5-1/15-19	–	–	64.5	–	23.6	–	–	–	–	–	–	–	–	–	–	–	–	–	11.8	–	–	110
6-1/64-71	–	–	82.7	–	1.5	0.5	–	0.5	0.5	–	–	–	–	–	0.5	–	–	–	13.9	–	–	202
6-4/27-32	–	–	42.6	–	21.3	0.5	–	0.5	–	–	–	–	–	–	–	–	–	–	35	–	–	197
8-1/42-48	–	–	80	–	13	0.5	–	0.9	–	–	–	–	–	–	–	–	–	–	5.6	–	–	215
11-1/38-45	–	–	65.5	–	20.5	4.4	–	1.7	–	0.6	0.6	–	–	–	–	–	–	–	6.7	–	–	180
15-1/69-71	–	–	70.4	–	20.8	0.5	–	0.5	–	–	0.5	–	–	–	–	–	–	–	7.4	–	–	216
17-1/70-77	–	–	60.6	–	29.9	1.6	–	1.2	–	0.4	–	–	–	–	0.4	–	–	–	6	–	–	251
21-1/40-47	–	–	29.1	–	32	13.8	–	0.5	0.5	–	–	–	–	–	–	–	–	–	23.6	0.5	–	203
25-1/42-49	–	–	55.3	–	19.4	–	–	0.9	0.5	–	–	–	–	–	–	–	–	–	24	–	–	217
27-3/23-30	–	–	45.8	–	27.3	0.8	–	0.8	–	–	–	–	–	–	–	–	–	–	25	0.4	–	260
30-3/73-80	–	–	72.8	–	15.8	2.6	–	2.2	–	–	–	–	–	–	–	–	–	–	6.6	–	–	228
34-1/39-46	–	–	59	–	16.1	0.8	–	0.4	–	–	–	–	–	–	–	–	–	–	23.3	0.4	–	249
37-1/63-107	–	–	55.8	–	20.9	3.4	–	1	–	–	–	–	–	–	–	–	–	–	18.4	0.5	–	206
39-2/95-99	–	–	74.3	–	10.4	2	–	0.5	–	–	–	–	–	–	–	–	–	–	12.4	0.5	–	202
42-2/0-7	–	–	41.8	–	49.1	0.6	–	2.4	–	–	–	–	–	–	–	–	–	–	5.5	0.6	–	165
46-2/47-54	–	–	58.2	–	32.8	–	–	0.4	–	–	–	–	–	–	–	–	–	–	8.2	0.4	–	244
47-1/113-120	–	–	72.6	–	10.1	–	–	0.5	–	–	–	–	–	–	0.5	–	–	–	16.2	–	–	197
50-1/0-7	–	–	50.6	–	35.1	0.4	–	0.4	–	–	–	–	–	–	–	–	–	–	13.1	0.4	–	245
52-1/50-57	–	–	46.5	–	28.4	–	–	0.4	–	–	–	–	–	–	–	–	–	–	24.8	–	–	226
53-2/4-11	–	–	26.8	–	34.2	–	–	–	–	–	–	–	–	–	–	–	–	–	39	–	–	41
54-4/23-26	–	–	53.5	–	32.5	2	–	1	0.5	–	–	–	0.5	–	–	–	–	–	8	2	–	203
55-1/91-98	–	–	15.3	–	1	0.3	–	1.4	–	–	–	–	–	–	1	–	–	–	80.1	0.3	0.3	287
56-4/60-67	–	–	4	–	1.8	0.4	–	–	–	–	–	–	–	–	0.4	–	–	–	92.9	0.4	–	226
58-2/107-114	–	–	63.3	–	3.7	0.5	–	0.5	0.5	–	–	–	–	–	–	–	–	–	31.2	0.5	–	218
59-1/117-124	–	–	39.1	–	3.2	0.3	–	–	0.3	–	–	–	–	–	–	–	–	–	56.8	0.3	–	317
60-1/8-15	–	–	58.5	–	12	–	0.4	2.4	–	–	–	–	–	–	0.8	–	–	–	23.1	2.8	–	250
Inner slope of Mariana Trench																						
Site 460																						
1-1/72-79	–	–	47.2	–	14.6	0.4	0.9	3	–	–	–	–	–	–	0.4	–	–	–	28.3	5.2	–	233
1-5/40-47	0.7	–	49.3	–	26.7	–	–	3.3														

3-5/37–44	–	–	71.2	0.5	12.7	2.9	–	2	0.5	–	–	–	–	–	–	–	0.5	–	8.8	0.5	0.5	205
4-1/90–97	–	–	69	–	11	0.5	–	2.5	–	–	–	–	–	–	0.5	–	–	–	16.5	–	–	200
4-3/30–37	–	–	68	0.5	9.9	2	–	2	–	–	–	–	–	–	0.5	–	–	–	15.8	0.5	1	203
4-6/5–12	–	–	62.7	–	0.4	3.2	–	1.8	–	0.4	–	–	–	–	–	–	–	–	31.2	0.4	–	284
5-1/30–37	–	–	62.5	–	7.9	3.1	–	–	–	–	–	–	–	–	–	–	–	–	26.2	0.4	–	229
6-1/80–87	–	–	71.3	–	10	1.9	–	0.5	–	–	–	–	–	–	–	–	–	–	15.8	0.5	–	209
6-2/20–27	–	–	52.7	0.5	11.9	1	–	3	–	–	–	–	–	–	1	–	–	–	21.9	8	–	201
7-1/79–86	–	–	1.5	0.5	3.4	–	–	1.5	–	–	–	–	–	–	–	–	–	–	92.6	–	0.5	203
8-1/37–44	–	–	22.1	2.1	10.5	0.3	0.7	3.9	–	–	–	–	–	–	0.3	–	–	–	59.6	0.3	0.3	286
Japan Sea																						
Leg 31, Site 299																						
1-1/101–110	–	–	28.6	–	19	4.8	–	9.5	–	–	–	–	–	38.1	–	–	–	–	–	–	–	21
2-5/97–104	–	1.7	15.1	–	59.7	8.4	–	12.6	–	–	–	–	–	–	–	–	0.8	–	0.8	0.8	–	119
3-3/91–95	–	1.1	17.4	–	4.5	11.1	2.8	38.2	0.6	–	–	1.7	0.6	–	1.7	–	0.6	5.1	10.1	5.6	–	181
5-1/80–87	–	–	5.5	–	73.3	1.8	–	15.8	0.6	–	–	–	–	–	0.6	–	–	1.2	0.6	0.6	–	165
7-2/104–108	–	–	50	–	9.2	30.1	–	5.3	–	–	–	–	–	–	–	–	–	–	2.9	2.4	–	206
8-3/80–87	–	–	23.9	–	13.7	23.6	–	4.2	0.4	–	–	0.7	–	20.4	0.7	–	–	–	6	6.3	–	284
9-5/70–74	–	–	46.7	–	13.6	29.6	–	5.9	0.6	–	–	–	–	–	–	–	0.6	0.6	1.8	0.6	–	169
11-6/58–65	–	–	16.2	–	5.4	8.1	–	5.4	–	2.7	5.4	–	–	54.1	–	–	–	–	2.7	–	–	37
12-3/20–24	–	–	0.9	–	4.7	2	–	0.9	0.1	0.5	–	0.1	–	90	–	–	–	–	0.6	0.2	–	131
12-4/48–52	–	–	34.8	–	28.3	19.6	–	7.6	–	–	–	–	–	7.6	1.1	–	–	–	–	1.1	–	92
14-5/16–20	–	–	15.2	–	54.4	8.8	–	9.6	–	–	–	–	–	9.6	–	–	–	0.8	0.8	0.8	–	125
16-1/106–110	–	–	6.9	–	62.3	12.7	1	3.9	0.5	–	–	0.5	–	–	0.5	–	0.5	0.5	1	9.8	–	204
17-3/78–82	–	–	31.7	–	51	5.5	–	4	0.5	–	–	–	–	–	0.5	–	0.5	0.5	2	4	–	202
19-1/86–90	–	–	17.3	–	7.4	7.4	–	1.2	–	–	–	–	–	60.5	–	–	–	–	6.2	–	–	81
20-2/126–130	–	–	5.8	–	11	74.5	–	5.1	–	–	–	0.7	–	–	–	–	–	0.7	1.5	0.7	–	137
22-2/80–87	–	–	7.9	–	54.2	15.4	–	11.9	0.4	–	–	0.4	–	–	1.3	–	0.9	1.3	4.8	1.3	–	227
24-2/110–117	–	–	12.4	–	21.9	9.5	–	8	–	–	–	–	–	0.7	–	–	–	–	39.4	8	–	137
28-1/126–130	–	–	20.7	–	15.3	28.4	1.4	17.1	0.5	–	–	0.5	–	9.8	–	–	0.5	0.9	3.6	1.4	–	200
29-1/134–138	–	–	16.3	–	10.2	12.2	–	8.2	–	–	–	–	–	46.9	–	–	–	–	6.1	–	–	49
30-3/46–53	–	–	37.1	–	19.4	9.7	–	6.5	–	–	–	–	–	16.1	–	–	–	–	11.3	–	–	62
31-2/25–32	–	–	16.7	–	–	–	–	–	–	–	–	–	–	33.3	–	–	–	–	50	–	–	6
32-2/72–79	–	–	18.2	–	–	9.1	–	9.1	–	–	–	–	–	3	–	–	–	–	–	–	–	11
33-2/57–64	3.6	–	–	–	–	3.6	3.6	10.7	3.6	–	71.4	–	–	3.6	–	–	–	–	–	–	–	28
35-1/76–80	–	–	8.2	–	3.6	49	3.6	26.8	0.5	–	–	1.5	0.5	–	0.5	–	0.5	0.5	3.6	1	–	194
36-4/88–95	–	–	2.8	–	3.4	3.4	2.3	0.6	–	–	–	–	–	85.2	–	–	–	–	2.3	–	–	176
37-3/60–67	–	–	7.5	–	2.5	–	2.5	10	2.5	–	70	2.5	–	–	–	–	–	–	–	2.5	–	40
38-4/53–60	–	–	–	–	–	5.3	7.9	7.9	–	–	–	–	–	65.8	–	–	–	–	2.6	10.5	–	38
38-5/107–111	–	–	–	–	1	31.4	19.1	11.8	0.5	–	0.5	0.5	0.5	18.6	1	–	0.5	0.5	7.8	6.4	–	204
Site 301																						
2-4/109–110	–	–	26.5	–	5.7	42.2	1.4	8.1	0.5	–	–	0.5	–	0.5	–	–	0.5	–	13.7	0.5	–	218
4-4/96–100	–	0.5	1.4	–	4.3	35.7	2.4	9.5	0.5	–	–	38.6	–	–	1	0.5	1	1	2.9	1	–	210
4-5/56–60	–	2.2	0.4	–	0.4	78.6	0.4	13.3	0.4	–	–	0.4	–	0.4	0.4		2.6		0.7	–	–	271
9-1/113–119	–	–	1.5	–	2.9	25	–	47.1	–	–	–	–	1.5	1.5	–	–	2.9	2.9	14.7	–	–	68
15-4/130–134	–	–	15.4	–	6.2	15.3	–	20	–	–	–	–	–	40	–	–	–	–	–	3.1	–	65
17-1/80–84	–	–	0.3	–	0.3	46	6	19.4	3.4	–	–	0.3	1	0.8	–	0.3	12.1	0.5	1.3	8.5	–	387

TABLE 2 (*continued*)

Core section/ interval (cm)		Clino- pyroxene		Ortho- pyroxene		Amphibole																
	Ol	Cpx_1	Cpx_2	Opx_1	Opx_2	Hb	Am	Ep	Grn	Cor	Per	Zr	Trm	Bi	Ap	Rut	Sph	Lcx	Mt	Ilm	Cr	No.
20-3/63–70	–	–	9.1	–	4	18.7	–	4.5	6.1	–	–	1	–	5	6.6	0.5	1	0.5	1.5	41.4	–	198
Outer slope of Japan Trench																						
Leg 56, Site 436																						
1-4/80–87	–	1.6	8.2	–	5.7	36.9	–	32.7	0.8	–	–	–	0.8	–	–	–	0.4	2.5	9	0.8	0.4	211
4-1/92–99	–	–	8	–	32.7	43.4	–	4.9	0.4	–	–	0.4	–	–	–	–	0.4	–	7.6	1.9	–	274
6-3/90–97	–	–	34.4	–	27.4	17.2	–	9.8	0.4	–	–	0.4	–	–	0.4	–	0.4	0.4	7.8	1.6	–	294
8-3/78–85	–	–	50	–	14.4	14.4	–	10	–	–	–	0.5	–	–	0.5	–	1	–	6	3	–	203
10-1/77–84	–	–	9.4	–	68.2	1.8	–	1.8	–	–	–	–	–	–	–	–	–	0.4	8.3	10.1	–	277
11-4/30–37	–	–	34	–	50	2.5	–	2	0.5	–	–	–	–	–	–	–	–	–	1.5	9.5	–	200
12-4/50–57	–	–	11.9	–	9.9	70.8	–	1.5	0.5	–	–	–	–	–	–	–	–	–	0.5	5	–	202
14-3/118–125	–	–	39.8	–	36.7	5.1	–	2.4	–	–	–	1	–	0.3	0.3	–	–	–	12.8	1.4	–	289
15-6/13–20	–	–	32.8	–	40.7	12.3	–	0.5	0.5	–	–	–	–	0.5	–	–	–	–	12.3	0.5	–	204
17-3/80–87	–	–	31.5	–	32	19	–	1.5	0.5	–	–	–	–	–	–	–	–	–	2	13.5	–	200
18-1/69–76	–	–	34.8	–	33.3	3.5	–	1.5	0.5	–	–	–	–	–	–	–	–	–	3.5	22.9	–	201
20-1/69–76	–	–	8	–	1	2.5	–	0.5	–	–	–	–	–	85	–	–	–	–	1.5	1.5	–	200
22-1/66–73	–	–	24	–	28.9	24.7	–	1.8	–	–	–	0.6	–	10.8	1.8	–	0.6	–	3	3.6	–	166
23-2/74–81	–	–	16.9	–	1.7	15.6	–	2.2	–	–	1.7	0.4	–'	0.4	0.4	–	–	–	40.3	20.3	–	231
25-1/37–44	–	–	34	–	10	8	–	4	–	–	–	–	–	30	–	–	–	–	14	–	–	50
27-1/117–124	–	–	5.5	–	32.9	16.4	–	2.7	–	–	6.8	1.4	–	13.7	–	–	–	–	12.3	8.2	–	73
29-1/54–61	–	–	23.4	–	10.3	10.8	–	1.1	–	–	–	–	–	–	–	–	–	–	45.1	9.2	–	184
30-1/94–101	–	–	6.4	–	5.8	51.3	–	–	–	–	1.3	–	–	28.6	0.6	–	–	–	5.8	–	–	154
31-3/77–84**	–	–	18.3	–	1.7	46.3	–	1.7	–	2.3	0.6	–	–	17.7	–	–	–	–	8.6	2.9	–	175
32-2/96–103**	–	–	52.9	–	12.5	6.7	–	1.9	–	–	1	–	–	3.8	–	–	–	–	21.2	–	–	104
33-6/88–95**	–	–	20.8	–	19.3	15.5	–	3.4	–	–	3.9	–	–	29	–	–	–	–	6.8	1.4	–	207
34-5/83–90**	–	–	51	–	4	2	–	4	0.5	–	–	–	–	1.5	–	0.5	–	–	36.5	–	–	200
36-4/92–99**	–	–	17.2	–	–	5.2	–	–	–	27.6	17.2	–	–	3.5	–	–	–	–	27.6	1.7	–	58
37-2/113–120**	–	–	6.5	–	–	–	–	–	–	1.9	52.8	–	–	16.7	–	–	–	–	20.4	1.9	–	108
38-2/77–84**	–	–	1.5	–	1.5	–	–	1.5	–	–	47.8	–	–	3	1.5	–	–	–	41.8	1.5	–	67
38-6/106–113**	–	–	10.2	–	7.1	12.2	–	1	–	–	6.1	–	–	–	–	–	–	–	54.1	9.1	–	98
39-1/106–113**	–	–	4.3	–	–	–	–	–	–	2.9	0.7	–	–	8	–	–	–	–	60.1	23.9	–	138
39-4/32–39**	–	–	7.3	–	2.7	0.9	–	0.9	–	2.7	3.6	–	–	1.8	–	–	–	–	75.4	4.5	–	110
40-2/72–79	–	–	43.9	–	9.8	2.4	1.2	2.4	1.2	–	–	–	–	–	–	–	1.2	–	23.2	14.6	–	82
40-4/63–70	–	–	10	–	–	10	–	–	–	–	–	–	–	10	–	–	–	–	40	30	–	10
40-6/75–82	–	–	4.5	–	–	18.2	–	–	–	–	–	–	–	4.5	–	–	–	–	45.5	27.3	–	22

Ol = olivine; Cpx_1 = brown clinopyroxene; Cpx_2 = green clinopyroxene; Opx_1 = colourless orthopyroxene; Opx_2 = brown orthopyroxene; Hb = brown and green amphibole; Am = pale green amphibole; Ep = epidote; Grn = garnet; Cor = corundum; Per = periclase; Zr = zircon; Trm = tourmaline; Bi = biotite; Ap = apatite; Rut = rutile; Sph = sphene; Lcx = leucoxene; Mt = Ti-magnetite; Ilm = ilmenite; Cr = Cr-spinel; No. = number of grains counted.

to depend less on biological processes in the seawater; furthermore, compared to other characteristics they better indicate the sources of sediments represented by them. TiO_2/Al_2O_3 mainly defines clastic sediment components and $(Fe_2O_3{}^* + MgO)/Al_2O_3$ is concerned with clastic and hydrothermal components.

For the mineralogical analyses, a 0.05–0.1 mm fraction was separated from the various sediments by wet sieving. Afterwards, heavy minerals were extracted from the fraction in 2.9 g/cm^3 of tribromomethane. The heavy minerals were identified using the petrographic microscope. The mineral composition was determined by counting more than 200 grains (when possible) for each analysis (Table 2). Authigenic minerals and lithoclasts were not counted. When necessary, mineral identification was carried out with the help of immersion oils, X-ray diffractometry and an electron microprobe analyzer.

By studying the mineral assemblages of sediments and comparing these assemblages with those of crystalline rocks, which are possible sources of the clastics, it was found that the genetic interpretation of the data might be improved if certain "untraditional" varieties (Opx_1, Opx_2, Cpx_1, Cpx_2, Hb and Am) could be distinguished in the mineral composition (see Table 2). The correctness of these distinctions was verified on the basis of the chemical characteristics defined by the microprobe analysis (Table 3 and Fig.1).

The results of heavy mineral analyses were obtained by using the following interrelationships:

(1) GM–MT–MF, where GM indicates minerals of granitic and acidic metamorphic complexes (zircon, tourmaline, monazite and staurolite), MT indicates common minerals from basic metamorphics such as greenschists and amphibolites (pale amphiboles, epidote, garnet, periclase, corundum and chloritized mafic minerals) and MF indicates common mafic minerals of magmatic rocks (olivine, all pyroxenes and green–brown hornblende).

(2) Ol–Cpx_1–Cpx_2–Opx_1–Opx_2–Hb, where Ol is olivine, Cpx_1 is brown (Ti-rich) clinopyroxene, Cpx_2 is green (Cr- or Fe-rich) clinopyroxene, Opx_1 is colourless (Mg-rich) orthopyroxene, Opx_2 is brown orthopyroxene, and Hb is green–brown (Ti-bearing) hornblende. All these minerals are components of MF.

As an initial approach, the GM–MT–MF interrelationship allows a major source of heavy clastics to be defined. Subsequent to this it is important to know the nature of the MF because the magmatic rocks serve as the most reliable indicators of the nature of modern active margins. An interpretation of the MF contents should be made by taking into account that: (1) all ultramafic rocks are characterized by the association olivine (0l)–green clinopyroxene (Cpx_2)–colourless orthopyroxene (Opx_1), (2) oceanic and marginal sea tholeiites and alkaline rocks commonly have a brown and green clinopyroxene (Cpx_1 and Cpx_2)–olivine (Ol) assemblage, but the Cpx_2 is far less abundant than Cpx_1, and (3) that volcanic rocks of the island arcs contain green clinopyroxene (Cpx_2), brown orthopyroxene (Opx_2), green–brown hornblende (Hb) and olivine (Ol) (the Ol percentage is always very low). In this last association, hornblende enriches arc volcanic rocks [such as the Japan, Ryukyu and Philippine Arcs (these will be termed the "western", or "ensialic", arcs below)] which have a relatively thick and sialic basement, whereas arc volcanic rocks with thin and simatic basement [such as Izu–Mariana, Yap and Palau ("eastern", or "ensimatic" arcs)] contain hornblende in very small amounts (Nechaev, 1987). Unfortunately, the hornblende may be metamorphic as well as volcanic (See Fig.1) and it is necessary in each case to take into account minerals associated with it.

The list of magmatic products presented above is far from complete. However, the rocks and heavy minerals included in this list are the most widely distributed on the active plate margins, have the greatest influence on the sediments, and, therefore, serve as good reference points for the interpretation.

Geodynamics of the North Pacific in the Quaternary and origin of active margin complexes

In the Quaternary sediments of the Central Pacific the heavy mineral association is characterized by a large proportion of the mafic component ($MF > 70\%$), a smaller quantity of basic metamor-

TABLE 3

Electron microprobe analyses of clastic minerals from sediment samples of the Deep-Sea Drilling Project

Leg	Site	Core section /interval (cm)	No.	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MgO	CaO	MnO	Na_2O	K_2O	Total
Olivine, 01														
59	447A	13-1/45–50	1	40.7	–	0.03	–	10.25	47.94	0.38	0.09	–	–	99.39
			2	40.48	–	0.03	–	10.87	47.12	0.40	0.13	–	–	99.04
			3	39.65	–	0.03	–	11.12	48.36	0.39	0.12	–	–	99.67
		12-2/67–70	4	39.32	0.01	0.06	–	9.42	50.96	0.16	0.16	–	–	100.1
60	453	1-1/106–113	5	37.55	–	–	–	26.94	34.34	0.22	0.5	–	–	99.55
			6	39.48	0.01	–	–	17.62	41.98	0.2	0.25	–	–	99.54
	459B	2-4/40–44	7	34.93	–	–	–	21.3	43.48	0.33	0.44	–	–	100.48
			8	36.46	–	–	–	22.02	39.57	0.35	0.47	–	0.01	98.89
Brown clinopyroxene, Cpx_1														
	291	2-1/124–131	1	52.25	1.28	3.03	0.07	6.47	15.16	20.21	0.2	0.4	–	99.07
59	447A	13-1/45–50	2	48.81	1.94	4.38	0.11	8.98	13.76	21.16	0.15	0.6	–	99.9
			3	48.09	2.22	6.14	0.07	9.55	12.28	21.58	0.16	0.51	–	100.61
59	447A	13-1/45–50	4	49.08	1.74	5.17	0.29	8.58	13.89	20.78	0.16	0.5	–	100.2
56	436	1-4/80–87	5	50.22	1.98	3.39	0.12	8.71	14.53	20.69	0.2	0.5	–	100.33
Green clinopyroxene, Cpx_2														
31	291	4-4/106–113	6	53.41	0.52	1.53	–	10.27	13.93	19.89	0.66	0.43	–	100.63
			7	50.87	0.31	0.93	–	12.45	13.45	19.91	0.8	0.29	–	99.01
		4-2/92–99	8	52.01	0.43	1.46	–	16.08	10.97	19	0.46	0.2	–	100.59
			9	52.25	0.34	1.83	–	11.78	13.76	19.36	0.44	0.3	–	100.06
		2-1/124–131	10	51.77	0.82	2.87	–	9.56	15.33	19.18	0.27	0.36	0.05	100.21
			11	50.29	0.22	4.41	0.42	6.69	15.55	21.86	0.18	0.21	–	99.83
	291A	1-6/84–91	12	52.27	0.33	1.06	–	12.47	13.08	19.94	0.66	0.26	–	100.07
59	447A	13-1/45–50	13	51.74	0.85	3.07	–	9.27	14.88	20.25	0.32	0.45	–	100.83
			14	53.3	0.31	2.59	0.98	4.38	18.27	20.31	0.06	0.29	–	100.51
			15	53.19	0.45	2.60	0.39	5.91	18.11	19.51	0.15	0.23	–	100.54
		12-2/67–70	16	48.91	0.29	2.03	0.65	4.64	22.17	20.36	0.17	0.21	–	99.43
59	450	5-4/38–45	17	50.61	0.43	2.34	–	12.18	14.49	19.95	0.46	0.25	0.02	100.72
		4-1/110–117	18	50.58	0.41	1.77	–	11.27	14.48	19.95	0.48	0.26	–	99.2
		3-6/88–95	19	50.17	0.37	1.6	–	10.26	14.88	21.77	0.6	0.23	0.01	99.89
			20	50.39	0.63	2.23	–	10.43	15.47	20.62	0.45	0.28	0.01	98.81
60	459B	60-1/8–15	21	52.07	0.53	2.33	–	9.26	14.98	20.35	0.65	0.3	0.02	100.51
			22	54.11	0.33	0.74	0.23	7.26	17.56	18.39	0.24	0.21	0.02	99.09
			23	52.46	0.4	3.2	–	9.47	16.03	18.85	0.32	0.21	–	100.95
			24	52.96	0.24	2.99	0.79	6.64	18.04	18.1	0.24	0.18	0.02	100.21
			25	51.34	0.09	2.04	–	11.21	14.01	20.53	0.4	0.28	0.01	99.92
			26	50.97	0.37	1.28	–	10.55	14.5	21.01	0.44	0.26	0.02	99.4
			27	53.35	0.25	2.3	–	6.59	18.3	18.59	0.24	0.17	–	99.79
		2-4/40–44	28	52.56	0.44	1.68	–	13.13	14.17	18.01	0.54	0.04	0.02	100.6
			29	51.58	0.48	0.46	–	9.94	16.44	20.2	0.38	0.34	0.02	99.84
			30	51.56	0.31	1.13	–	14.5	12.68	18.49	0.85	0.23	–	99.75
60	459B	2-4/40–44	31	50.8	0.17	3.14	–	4.17	16.91	23.59	0.14	0.1	–	99.02
			32	51.6	0.16	2.69	–	4.32	16.98	23.13	0.15	0.15	–	99.19
	460	8-1/37–44	33	52.36	0.2	1.07	–	10.81	13.83	20.87	0.71	0.25	0.02	100.11
			34	52.15	0.36	1.9	–	11.22	15.05	19.44	0.39	0.18	–	100.7
		4-6/5–12	35	51.83	0.15	1.7	0.24	3.59	17.1	25.21	0.11	0.1	–	100.02
			36	52.92	0.22	2.65	–	9.12	14.56	19.98	0.3	0.27	–	100.02
			37	52.25	0.39	2.94	–	8.1	16.07	18.92	0.26	0.19	–	99.12
		1-1/72-79	38	53.27	0.27	1.43	–	6.65	16.35	22.23	0.23	0.15	0.02	100.42
			39	50.12	0.32	4.28	0.21	4.99	16.03	23.4	0.11	0.13	–	99.59
31	299	2-5/97–104	40	49.37	–	1.61	–	10.06	19.27	18.97	0.46	0.14	0.02	99.9
	301	2-4/105–110	41	51.5	0.16	1.19	–	9.88	14.86	21.55	0.39	0.25	–	99.76

TABLE 3 (*continued*)

Leg	Site	Core section /interval (cm)	No.	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MgO	CaO	MnO	Na_2O	K_2O	Total
			42	49.35	0.36	4.03	0.34	4.78	16.1	24.06	0.08	0.22	–	99.32
			43	51.1	0.21	1.86	–	9.09	14.89	22.2	0.49	0.28	–	100.12
56	436	40-4/63–70	44	52.8	0.3	2.6	0.08	7.19	17.56	19.93	0.17	0.32	–	100.94
56	436	40-2/72–79	45	52.34	0.47	2.18	–	10.38	14.29	20.11	0.33	0.32	–	100.42
		38-6/106–113	46	51.95	0.31	2.24	0.05	11.77	17.06	16.68	0.31	0.06	–	100.45
Colourless orthopyroxene, Opx_1														
60	460	8-1/37–44	1	54.59	0.26	3.63	–	5.46	35.36	0.82	0.14	–	–	100.26
			2	54.38	0.01	1.91	0.6	5.39	34.73	2.26	0.16	–	–	99.44
			3	54.41	0.01	2.28	0.63	5.63	35.58	0.55	0.15	–	–	99.23
Brown orthopyroxene, Opx_2														
31	291	4-4/106–113	4	54.22	0.37	1.07	–	18.15	24.35	1.73	0.5	0.08	–	100.47
		4-2/92–99	5	53.65	0.27	0.76	–	21.39	21.45	1.62	0.81	0.05	–	100
	291A	1-6/84–91	6	54.54	0.18	0.67	–	18.97	23.79	1.11	1.3	0.04	0.02	100.62
60	459B	60-1/8–15	7	54.09	0.21	0.78	–	21	21.2	1.43	0.81	0.04	0.01	99.57
			8	53.43	0.27	0.99	–	23.01	19.81	2.15	0.94	0.06	–	100.67
		2-4/40–44	9	51.1	0.33	0.84	–	24.14	20.46	1.91	1.05	0.05	0.02	99.9
			10	55.67	0.25	1.42	–	17.42	22.12	1.55	0.8	0.05	0.01	99.29
60	460	8-1/37–44	11	51.1	0.23	0.47	–	28.24	16.64	1.61	1.58	–	0.02	99.89
			12	52.99	0.22	0.99	–	18.99	24.33	1.49	0.9	–	–	99.91
			13	51.96	0.15	0.5	–	24	20.59	1.11	1.52	0.05	0.01	99.89
		1-1/72–79	14	52.34	0.23	1.49	–	16.16	27.45	1.48	0.62	0.04	–	99.82
			15	50.83	0.3	0.96	–	23.51	20.91	2.01	0.87	0.06	–	99.45
31	299	2-5/97–104	16	52.14	0.19	1.18	–	20.69	22.81	1.55	0.82	–	–	99.38
	301	18-4/6–10	17	56.26	0.01	0.97	–	16.08	23.96	1.11	0.47	0.2	–	99.06
		2-4/105–110	18	51.71	–	1.36	–	24.4	20.06	0.73	1.62	–	–	99.87
			19	52.9	–	0.8	–	21.5	22.1	1.51	0.83	–	–	99.63
			20	50.91	–	0.78	–	25.04	19.84	0.73	1.76	–	–	99.06
56	436	40-2/72–79	21	53.37	0.23	0.64	–	21.4	22.05	1.41	1.23	0.06	–	100.39
Hornblende, Hb														
31	291	4-4/106–113	1	46.77	1.85	9.64	–	12.18	13.54	10.96	0.4	1.92	0.25	97.51
60	453	1-1/106–113	2	43.66	1.92	12.42	0.16	13.81	11.63	12.27	0.1	1.32	1.69	98.98
60	459B	54-4/23–26	3	48.01	0.9	7.34	–	15.95	14.51	9.88	0.74	1.23	0.1	98.66
	460	8-1/37–44	4	48.92	1.42	7.34	–	13.65	14.59	10.33	0.54	1.21	0.19	98.17
		1-1/72–79	5	47.09	1	8.99	–	18.28	8.43	11.09	0.57	1.45	1.28	98.18
31	299	38-5/107–111	6	43.97	1.37	8.19	–	16.93	14.62	10.31	0.53	1.6	0.38	97.9
			7	46.37	1.19	7.35	–	12.23	18.37	10.97	0.45	1.12	0.41	98.46
			8	44.62	1.71	8.02	–	21.29	9.42	10.56	0.36	1.37	0.78	98.13
			9	44.06	2.36	10.18	0.02	11.14	15.34	10.67	0.2	4.02	0.14	98.13
			10*	48.1	2.09	7.83	–	9.24	17.67	12.16	0.11	0.96	0.71	98.87
			11*	46.61	1.35	6.96	–	15.5	14.3	11.07	0.26	0.89	0.56	97.49
			12*	41.3	2.18	13.24	–	10.62	16.51	10.84	0.15	2.45	0.46	97.74
			13*	45.21	1.79	8.27	–	17.37	12.86	11.12	0.44	1.18	0.83	99.07
			14*	45.43	2.05	8.78	–	17.13	13.06	10.97	0.36	1.03	0.77	99.58
		9-5/70–74	15*	42.88	2.01	11.11	–	11.35	17.36	10.8	0.2	2.2	0.31	98.22
		2-5/97–104	16	43.98	1.82	8.23	–	14.07	17.12	10.62	0.39	1.45	0.75	98.43
31	299	2-5/97–104	17	41.73	2.55	8.63	–	13.95	17.7	10.71	0.39	2.57	0.33	98.56
	301	18-4/6–10	18	43.27	1.82	12.57	–	8.37	16.79	12.36	0.08	1.88	0.62	97.76
		2-4/105–110	19	46.18	0.97	7.39	–	16.31	13.42	10.79	0.62	1.23	0.35	97.26
			20	46.5	0.96	7.37	–	17.03	12.6	10.67	0.75	1.44	0.36	97.69
56	436	38-6/106–113	21	49.55	1.36	6.32	–	13.95	14.35	10.6	0.55	1.47	0.11	98.27

TABLE 3 (*continued*)

Leg	Site	Core section /interval (cm)	No.	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MgO	CaO	MnO	Na_2O	K_2O	Total
Meta-amphibole, Am														
60	459B	60-1/8–15	22	50.31	0.56	1.37	–	22.26	11.38	11.47	0.17	0.13	0.01	98.2
	460	8-1/37–44	23	52.43	0.18	3.42	–	12.36	17.85	10.99	0.35	0.07	0.18	97.84
			24	52.4	0.13	3.24	0.06	14.44	14.5	12.04	0.22	0.41	0.08	97.49
	460	1-1/72–79	25	53.42	0.19	3.59	0.08	13.51	14.52	11.94	0.78	0.14	0.1	98.19
			26	51.43	0.42	3.33	0.09	17.08	23.97	1.68	0.61	0.05	0.01	98.67
31	299	38-5/107–111	27	52.81	0.23	2.21	0.02	24.38	15.6	2.06	0.74	0.27	0.03	98.35
			28	55.45	0.01	1.44	–	16.18	24.46	1.47	0.49	0.06	0.01	99.56
			29	50.27	0.25	1.61	–	30.21	13.15	1.71	1	0.16	0.05	97.87
31	299	38-5/107–111	30	53.78	0.05	1.36	–	20.81	20.44	0.91	0.4	0.11	–	97.3
			31	57.44	0.01	0.16	–	1.73	25.58	12.96	0.14	0.14	–	98.14
			32	48.84	0.39	6.73	–	10.61	18.68	11.15	0.35	1.32	0.19	98.26
			33	46.72	0.4	11.51	0.46	9.22	16.2	10.94	0.23	3.02	0.33	99.03
			34	41.74	0.43	13.54	–	12.84	13.92	11.34	0.18	2.91	0.46	97.37
			35	44.46	0.54	11.99	–	9.32	17.32	12.6	0.22	2.49	0.36	99.29
			36	43.77	1.04	14.95	–	8.87	16.09	11.31	0.16	2.14	0.37	98.44
	299	2-5/97–104	37	39.48	1.89	12.65	0.04	15.65	15.14	10.36	0.21	2.4	0.3	98.12
	301	18-4/6–10	38	55.81	–	2.2	0.05	10.05	16.43	12.62	0.25	0.65	0.14	98.2
			39	54.46	–	3.08	–	9.68	17.82	12.39	0.33	0.58	0.24	98.58
			40	56.59	–	2.55	0.25	7.75	19.9	12.16	0.24	0.33	0.03	99.8
			41	55.92	–	2.98	0.4	7.77	19.78	11.52	0.1	1.17	0.24	99.89
			42	55.84	–	1.76	–	5.27	21.2	13.48	0.06	0.38	0.21	98.2
			43	47.41	0.43	9.48	0.11	9.8	15.41	12.35	0.11	1.27	0.92	97.26
31	301	2-4/105–110	44	53.98	–	1.26	–	14.75	14.01	13	0.68	–	0.05	97.73
			45	45.34	0.2	12.33	0.3	9.02	15.71	12.19	0.12	2.64	0.27	98.12
			46	45.75	0.82	10.68	0.06	13.71	13.06	11.83	0.32	1.52	0.41	98.17

*Reddish brown hornblende (others are brown and green).

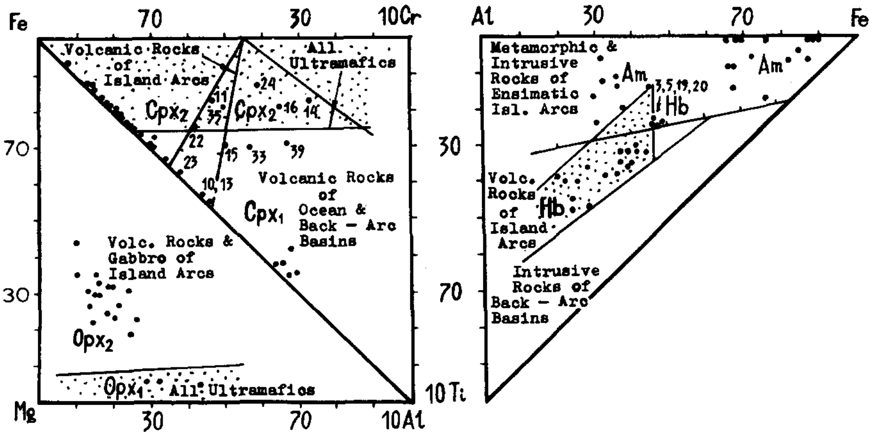

Fig.1. Comparison between minerals from sediments (points) and certain crystalline rocks (fields) on the basis of their chemical characteristics. Mineral abbreviations are the same as those in Table 2; point numbers are the same as those in Table 3. The data for 115 orthopyroxenes (Opx), 226 clinopyroxenes (Cpx) and 54 amphiboles (Am and Hb) from the crystalline rocks are from Bloomer and Hawkins (1983), Bougault et al. (1982), Chen (1978), Chen (1984), Dick et al. (1980), Dixon and Batiza (1979), Dmitriev (1980), Dobretsov et al. (1980), Fodor and Klaus (1975), Fodor and Rosendahl (1980), Fodor et al. (1980), Imino (1986), Ishii (1981), Kuroda and Shiraki (1975), Mattey and Muir (1980), Mattey et al. (1981), Meijer et al. (1982), Natland (1982), Ridley et al. (1974), Sakuyama (1979), Savelyeva et al. (1980), Scott (1981), Sharaskin (1982), Sharaskin et al. (1980), Thompson and Humphris (1980), Vysotsky (1989) and Zakariadze et al. (1981). In addition, thirteen analyses of clinopyroxenes from basalts of the Japan Sea region (V. Sjedin, pers. commun., 1988) were also used. Analyses of groundmass crystals from volcanic rocks and crystal rims were not used here.

phic clastics (MT), and a lack of granitic and acidic metamorphic indicators (GM) (Fig.2). $Ol+Cpx_1$ predominates in the MF, indicating the dominant influence of oceanic volcanic sources. The Opx_2–Cpx_2–Hb association shows that minerals of the ensialic arcs and active continental margins dominate among the minor heavy clastics. However, it should be remembered that the studied areas cover mainly the zones of volcanic and tectonic activity and seamounts in the ocean, and the passive basins *near* these zones. Meanwhile, passing from the seamounts into the basin a tendency for an increasing arc pyroclastic component among the entire MF component was noted. The arc pyroclastics probably dominate in sediments of the central oceanic areas far from the

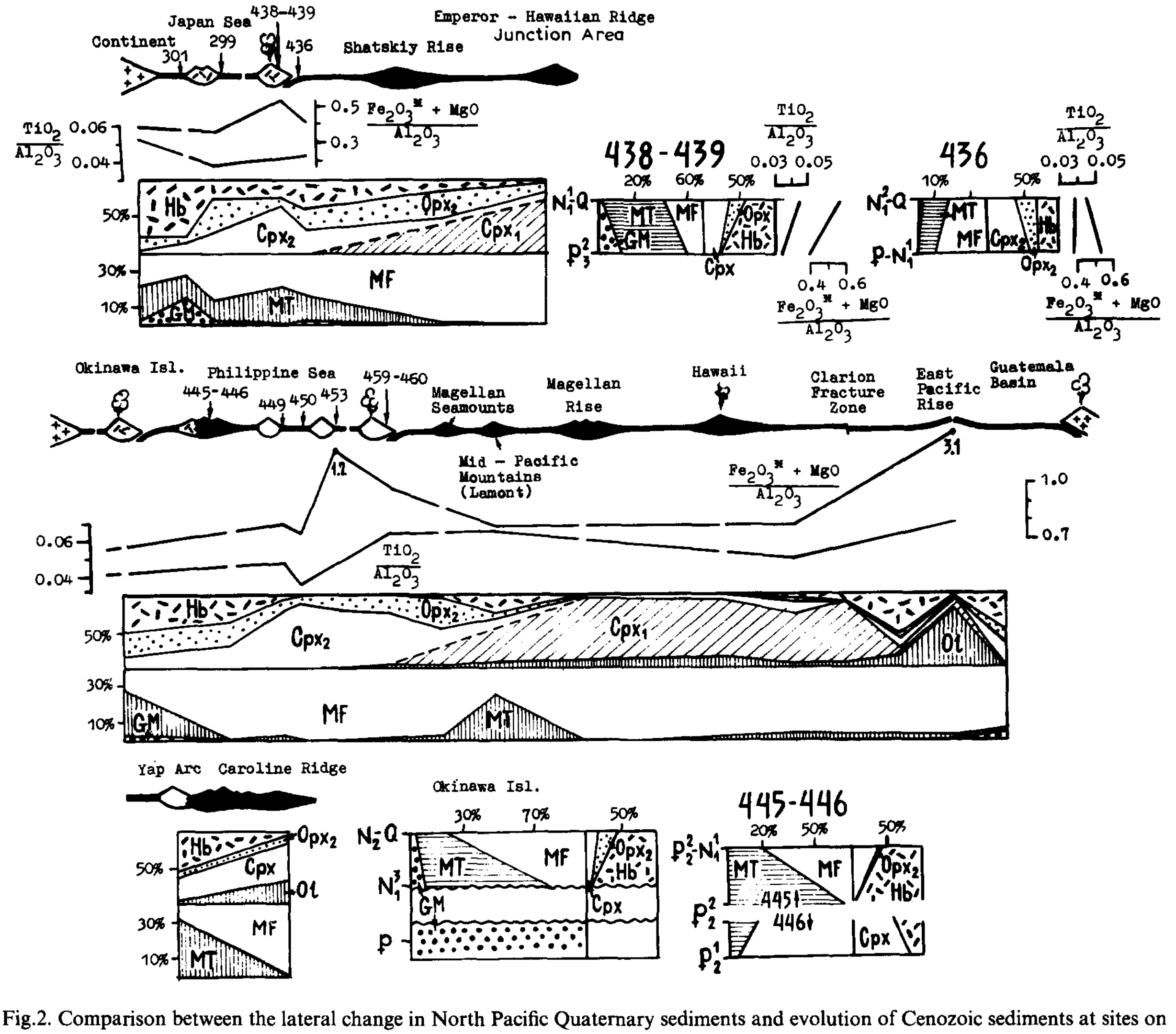

Fig.2. Comparison between the lateral change in North Pacific Quaternary sediments and evolution of Cenozoic sediments at sites on the Northwestern Pacific margin on the basis of average chemical and mineral interrelationships. Mineral abbreviations are the same as in Table 2. GM = indicators of granitic and acidic metamorphic rocks (Zr, Trm, monazite and staurolite); MT = minerals of basic metamorphic rocks (Am, Ep, Grn, Per and Cor); MF = mafic magmatic minerals (Ol, Px and Hb). Only chemical analyses of clays and argillaceous sediments were applied here. In addition to the original data, the data of Murdmaa et al. (1980), Murdmaa and Kazakova (1980), Repechka and Gramm-Osipov (1975), Sato (1980), Sato and Suzuki (1977), Sugisaki (1980), Suzuki (1975), Voronova et al. (1980) were used. *All Fe as Fe_2O_3. Translation of Soviet chronological symbols used in figures: P_2^1 = early Eocene; P_2^2 = middle Eocene; P_2^3 = late Eocene; P_3^1 = early Oligocene; P_3^2 = late Oligocene; N_1^1 = Early Miocene; N_1^2 = Middle Miocene; N_1^3 = Late Miocene; N_2 = Pliocene; Q = Quaternary.

active zones and mountains. Deposition of arc clastics in the deep ocean probably involves volcanic explosions and pumice drift (pumice with a two-pyroxene phenocryst assemblage is not unusual in the ocean).

The proportion of arc pyroclastics (Opx_2–Cpx_2–Hb) in sediments increases from the Central Pacific towards both the American and Asian continents, and at distances of ~1000 km from arcs and from active continental margins generally, they predominate over oceanic clastics (Fig.2).

As would be expected, arc volcaniclastics are abundant throughout the margin regions. The mafic component consists mainly of Hb, Opx_2, Cpx_2 and, in small amounts, Ol near and within the ensialic arcs (sketches of arcs symbol with dashes in Fig.2) and of Opx_2, Cpx_2 (with almost no Ol or Hb) near and within the ensimatic arcs (sketches of arcs without dashes). This difference in arc sediments was not the only difference observed. The sediments from the ensimatic arc zone, in contrast to those from the ensialic zone, contain only very small amounts of the granitic and acidic metamorphic indicators (GM). The highest contents of GM are found in sediments near the continents.

Touching upon the chemical characteristics it should be noted that (1) from the centre of the ocean to both the continents the contents of mafic elements (Ti, Fe and Mg) decrease, forming a background to all other lateral changes in the chemical characteristics of the sediments, (2) both oceanic and back-arc zones of the spreading and, to a lesser degree, fore-arc regions are distinguished by a greater iron content in the sediments, related undoubtedly to hydrothermal activity, and (3) in Western Pacific seamounts (extinct volcanoes), sediments contain much titanium and relatively little iron and magnesium, which is characteristic of primary alkaline volcanic rocks.

On only one occasion is there deviation from these relationships: at the junction between the Yap Arc and the Caroline Ridge the sediments contain abnormally high contents of MT and Hb (on the basis of analyses from Murdmaa et al., 1980) (see Fig.2). In this case, because no hornblende-bearing volcanic rocks were observed, the hornblende is metamorphic rather than volcanic; hornblende-rich metamorphic rocks are quite abundant (Hawkins and Batiza, 1977; Savelyeva et al., 1980) in this area of plate collision (Egushi, 1984). The state of unreleased stress which is prevalent at the Yap Arc–Caroline Ridge junction results in pushed-up blocks of basement exposing metamorphic rocks in a zone of erosion. Elsewhere on the Northwestern Pacific margin either a tensional or unstressed environment dominates (Brooks et al., 1984).

From the foregoing, it can be said that heavy clastic mineral assemblages closely reflect geological conditions:

(1) An oceanic volcanic rock association characterizes the central part of the ocean.

(2) Island arc volcaniclastics dominate in active oceanic and continental margins where uninhibited subduction takes place (Mariana-type subduction, with weak plate coupling; see Uyeda and Kanamori, 1979).

(3) Metamorphic clastics become significant in cases of collision and, perhaps, in cases where subduction is hindered (Chilean-type, with strong plate coupling).

(4) The hornblende-rich arc volcaniclastics indicate ensialic arcs, and the hornblende-poor volcaniclastics indicate ensimatic arcs.

(5) The granitic and acidic metamorphic clastics (GM) are characterized by a sialic component similar to that of the earth's crust.

(6) High levels of $(Fe_2O_3^* + MgO)/Al_2O_3$ in the sediments reflect hydrothermal activity at the spreading ridges.

By comparing spatial changes in sediment type with temporal changes one can understand how a given section of a recent subduction zone–arc–back-arc basin complex develops. In this respect, Site 436, which is located on the outer slope of the Japan Trench (Fig.2), is of special interest. Using data from ash layer distribution at Sites 438/439 (on the inner slope of the Japan Trench) and 436, and taking into account previous reconstructions of the migration of the Pacific plate, Fujioka (1983) proposed that Site 436 moved at least 3000 km from the Central Pacific to the Japan Trench during the Paleogene–Quaternary period. The data presented only partly support this proposition (Fig.2). The mineralogical and chemical characteristics of the Site 436 sediments change in time in a fashion which is similar to the changes observed in the Quaternary sediments from the Central Pacific to the Japan Arc: MT and Opx contents increase and $(Fe_2O_3{}^* + MgO)/Al_2O_3$ decreases. However, the typical oceanic heavy mineral assemblage (Ol and Cpx_1) and chemical characteristics ($TiO_2/Al_2O_3 > 0.4$; $(Fe_2O_3{}^* + MgO)/Al_2O_3 > 0.8$) are not found in the Site 436 clays. This suggests that the movement of Site 436 was not exactly in the manner that Fujioka (1983) proposed. These data can only be explained in the framework of long-lasting W-facing subduction.

The Paleogene–Quaternary decrease in GM content and the increase in TiO_2/Al_2O_3 and $(Fe_2O_3{}^* + MgO)/Al_2O_3$ on the Japan Arc and Okinawa Island [on the basis of data from Murdmaa and Kazakova (1980), Sugisaki (1980) and Sato and Suzuki (1977)] undoubtedly indicate that the Japan and Ryukyu Arcs are ensialic (Fig.2).

At Sites 445 and 446 (Fig.2) the heavy mineral interrelationships which were obtained on the basis of the data of Sato (1980), show that in the early Eocene this region was located in the central part of the ocean. In the middle Eocene it was located in a position reminiscent of the Caroline Ridge–Yap Arc junction, where the Quaternary sediments bearing anomalously high contents of MT and Hb occur. The Philippine Sea is known to have also formed in the middle Eocene. It has been proposed that the parental nucleus of the sea (its western basin with the adjacent ridges in the north) formed by (1) entrapment of an oceanic part after the direction of the migration of the Pacific plate changed (Uyeda and Ben-Avracham, 1972) or (2) as a part of the Indonesian–Philippine complex (Karig, 1975). The data presented are consistent with both ideas, and suggest that the oceanic ridge–arc collision resulted in the entrapment. On the basis of the activity of the eastern arcs separating the sea from the ocean, which began between 48 and 45 Ma (Seno and Maruyama, 1984), this collision was the *cause* of the change in direction of the plate movement.

Thus, the present-day margin complex is heterogeneous: its eastern section (the Izu–Mariana–Palau Arcs and the entire Philippine Sea) has simatic oceanic nucleii, whereas the western part (the Japan–Philippine Arc together with its back-arc region) has sialic continental nucleii.

Geodynamic models of active margin development

Philippine Sea

Like the Quaternary sediments of the region (Fig.2), the older sediments contain almost no granitic or acidic metamorphic indicators (Fig.3). Major events are indicated by changes in the MT/MF ratio. In almost all cases MF comprises island arc clastics (Opx_2–Cpx_2–Hb–Ol). It should be noted here that the hornblende is not always volcanic: the data of Fig.1 and Table 3 suggest that the metamorphic green–brown hornblende is not unusual in sediments and in crystalline rocks of island arcs. In certain cases the MF contains minerals from ophiolitic basalts (Ol–Cpx_1) and ultramafic rocks (Ol–Opx_1–Cpx_2). The highest MT content is found in the lower part of the middle Eocene sediments of Site 445 (Sato, 1980). The oceanic ridge–arc collision was at its peak in the early middle Eocene and resulted in the second "echelon" (part) of the subduction zone–island arc–back-arc basin complex in the Philippine Sea region. Perhaps this process made possible the transfer of the plate tectonic stress from one echelon to another, so that subsequently the system was considerably less prone to plate tectonic "crises".

Sediments show reduced basement erosion, which is connected with compressive geodynamic regimes in the region at the end of Eocene in the second half of the Oligocene and the first half of the Early Miocene, and at the end of the Miocene. The increase in the MT content in the early middle Eocene was probably related to tectonic dislocations induced by the change in motion of the Pacific plate. This event was ubiquitous and simple. The following compressive regime, however, was more complicated. Widespread and significant increases in MT and the Ol–Cpx_1 association of the MF occurred in the western part of the Philippine Sea (Sites 291, 445 and 447), while in the eastern part (Sites 449, 459 and 460) only two weak peaks in the MT, at the beginning and at

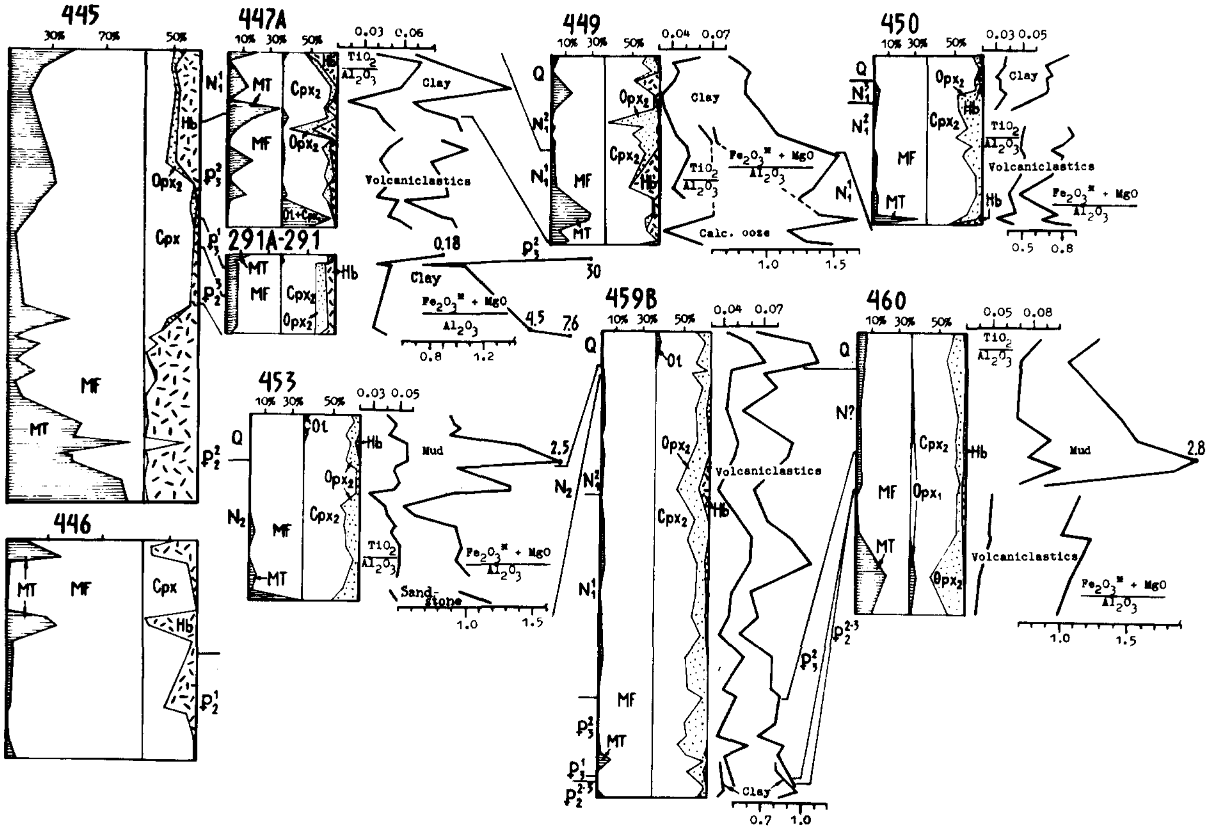

Fig.3. Mineralogical and chemical interrelationships in sediments of the Philippine Sea. Mineral abbreviations are the same as Table 2 and Fig.2. Vertical scale is not constant. The data of Sites 445 and 446 were taken from Sato (1980). *All Fe as Fe_2O_3.

the end of this period, were noted. It may be inferred that, in the western echelon of the margin system, collision and impeded subduction took place during this period.

An abrupt increase in the metamorphic debris in the Late Miocene was recorded at all sites where sediments of this age were preserved. (Note that in many cases the Late Miocene sediments are reduced or absent.) Perhaps collisions in both echelons of the system occurred at this time.

The data presented in Fig.3 also reveal the relationship between the volcanic events in the western ensialic and the eastern ensimatic arcs surrounding the Philippine Sea. This relationship could be ascertained by virtue of the following: (1) The volcanoclastics of these arcs can be distinguished on the basis of the Opx/Hb ratio (Opx/Hb >1 in the eastern clastics and <1 in the western clastics; see Fig.2), and (2) in the central part of the Philippine Sea (Sites 291 and 447–450) pyroclastic fragments from both arcs were major components of the heavy clastic mineral assemblages throughout the entire duration of the deposition of the assemblages.

If the volcanic activity of the arcs were constant one would expect that at each point in the Philippine Sea, and passing upwards through the column, the sediments would contain progressively smaller amounts of clastics of the eastern arc, from which sections of the Philippine Sea are being removed as a result of the back-arc spreading, and progressively larger amounts of clastics of the western arc, towards which the Philippine Sea is being drawn as a result of spreading and subduction related to these arcs. The reality is more complicated. Volcanic clasts from the eastern arc dominated in sediments of the central Philippine Sea (Sites 291 and 447–450) from the middle Eocene to the beginning of the late Oligocene, from the end of the Early Miocene to the Middle

Miocene, and in the Quaternary. In intermediate periods, excluding collisional periods, the hornblende-rich clastics from the western arc dominated in the central Philippine Sea. It may be concluded that the arc volcanism was occasionally transferred from one echelon of the margin system to another. Some of these transfers occurred during the collisional periods (Fig.4).

By combining the data from this paper with those from previous publications (e.g., Uyeda and Ben-Avracham, 1972; Karig, 1975; Hussong and Uyeda, 1981; Scott, 1983; Seno and Maruyama, 1984), new details of the development of the Philippine Sea may be proposed (Fig.4). This geodynamic model is characterized by the conception of the en-enchelon marginal complex as a

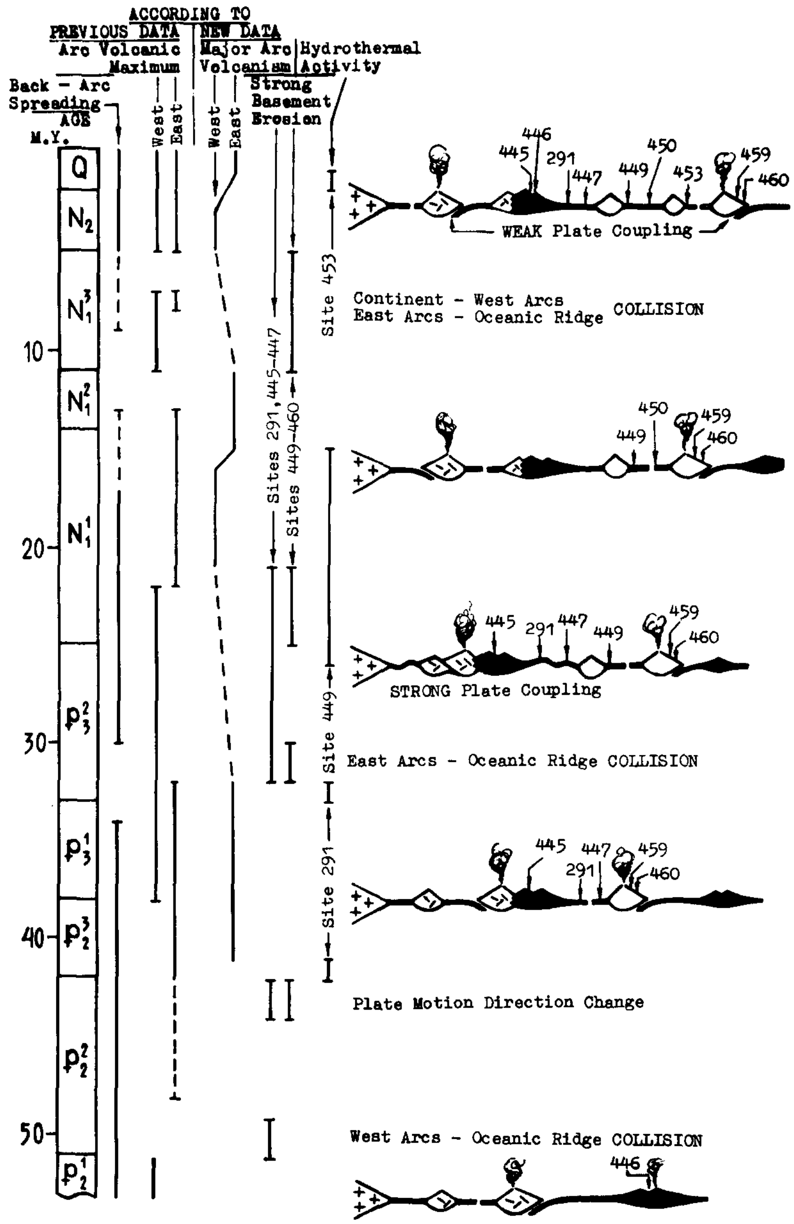

Fig.4. Summary of previously published and new data on the history of the Philippine Sea and the geodynamic profile illustrating the model of the development of the Philippine Sea.

complete system with a variety of "states" (stages). These states are distinguished by the number and orientations of the echelons, each of which consists of a subduction zone, island arc and back-arc basin. One of the main "functions" of the system is the release of plate tectonic stress. All processes in each echelon (subduction, arc volcanism and back-arc spreading) are controlled by the mode of subduction, as has been proposed by Karig (1975) and Uyeda and Kanamori (1979). The thickness and rigidity of the subducted lithosphere exert a significant influence on the mode of subduction. Further, in the echelon where the subduction environment is more favourable, the processes are more intense. The data presented here allow us to judge the relative activity of the echelons with respect to their arc volcanism. If subduction is blocked by thick, rigid lithosphere, it is carried from place to place together with the related arc magmatism and back-arc spreading and thus the state of the system changes. In such complexes, back-arc lithosphere is short lived because it can be subducted.

Therefore, the island arcs and, perhaps, continental margins accumulate and preserve the material generated in the active margin.

High $(Fe_2O_3^* + MgO)/Al_2O_3$ and relatively low TiO_2/Al_2O_3 contents in the sediments allow us to define the temporal and spatial distribution of the hydrothermal activity. This activity is found in the area of Site 291 at the beginning of the late Eocene and late Oligocene, near Site 449 at the end of the Oligocene and during the Early Miocene, and near Site 453 between the Pliocene and the Quaternary (Figs.3 and 4). Hydrothermal activity may also have occurred near Site 460 at the Oligocene/Miocene transition. All these events happened in active zones of the margin system when tension conditions prevailed. Hydrothermalism occurred especially frequently in zones of active back-arc spreading.

The Japan Sea

Figures 5 and 6 show data on the development of the Japan Sea. This marginal complex differs from the Philippine Sea complex because it is so simple (it comprises just one echelon). What causes this difference? Perhaps the Japan Sea system was never subjected to a strong collision like that in the Philippine Sea area 50–48 Ma ago. (However, having said this, perhaps collision between the Japan Arc and the Emperor Ridge (Northwestern Pacific) may occur in the future.) In other respects, the history of the Japan Sea complex is similar to that of the Philippine complex. In particular, there were reorientations of the structure of the former causing subduction both at times when oceanic lithosphere prevailed and at other times when back-arc lithosphere was dominant. The Early Miocene westward migration of the volcanic arc chain was probably due to reorientation rather

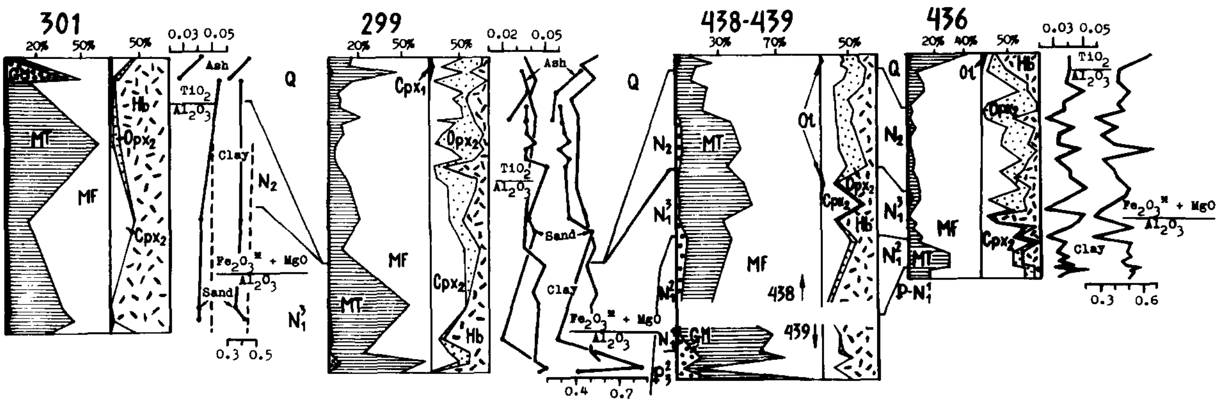

Fig.5. Mineralogical and chemical interrelationships in sediments of the Japan Sea. Mineral abbreviation;s are the same as in Table 2 and Fig.2. Vertical scale is not constant. The data of Sites 438 and 439 are taken from Murdmaa and Kazakova (1980). *All Fe as Fe_2O_3.

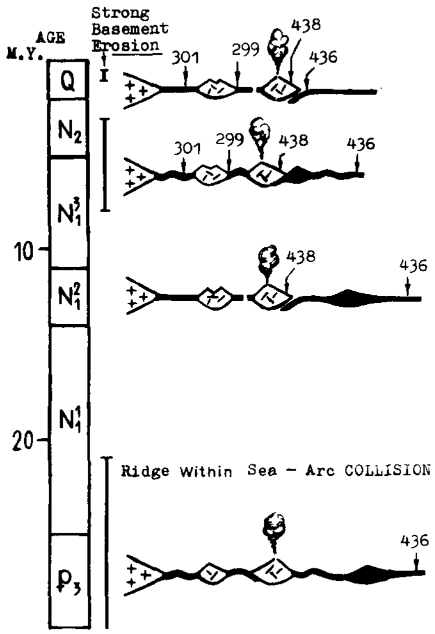

Fig.6. New data on the history of the Japan Sea and the geodynamic profile illustrating the model of the development of the Japan Sea.

than to the step of the Japanese subduction zone to the west, as Moore and Fujioka (1980) proposed. This also causes a delay in the drift of Site 436 to the Japan Arc, as noted earlier.

It should be remembered that the models advanced here suffer from a lack of data, and it should be clear that the actual situation is much more complex than that shown in Figs.4 and 6. The states, and especially the regimes, certainly changed more often in both time and space. Nevertheless, the data presented do enable the formulation of possible explanations in general terms, for the dynamics and evolution of active margins.

Lithological evolution of the active margin

By comparing the data presented in Figs.2–6 one finds that the material in ensialic and ensimatic marginal complexes converges with time. This evolution appears in the form of increasing basicity in the former and in the form of decreasing basicity in the latter. The indicators of convergence are as follows:

(1) Throughout the active margin the proportions of arc volcaniclastics (Opx_2–Cpx_2–Hb) increase. In the case of ensialic development (Okinawa Island, Sites 299, 301, 438 and 439 in Figs.2, 5 and 6) the volcaniclastics replace the combination of granitic and various metamorphic clastics (GM + MT), and in the case of ensimatic development (Sites 445 and 446 in Fig.2 and all sites in Figs.3 and 4) they replace the combination of oceanic magmatic and metamorphic clastics ($Ol + Cpx_1 + Opx_1 + MT$). Arc magmatism appears as the major process generating new lithosphere in the active margin.

(2) Within the arc volcaniclastic deposits near the ensialic arcs (Okinawa Island, Sites 299, 438 and 439) the percentage of hornblende decrases with time, while near the ensimatic arcs (Sites 459 and 460) it is constantly low. A comparable decrease in the Hb/Px ratio in the volcaniclastics of the ensialic arcs on the western and northern edges of the Philippine Sea (Sites 292 and 296) can be observed by averaging Donelly's (1975) data (Nechaev, 1987; Nechaev and Derkachev, 1989).

The mineralogical change in the arc volcaniclastics can be understood if it is remembered that hornblende usually enriches the acidic, water-bearing magmas which are characteristic of thick, sialic lithosphere. The ensialic evolution of the active margin leads to thinning and basification of the initial continental lithosphere; this process is represented by the arc magmatic products, in particular the volcaniclastics.

In the case of ensimatic development, the influence of the parental oceanic lithosphere is much less strong and no distinct evolutionary changes in the volcanic material are observed.

It seems that the arc magma tends to lose the characteristics that the initial lithosphere of the corresponding arc imprinted upon it. The thicker the lithosphere, the greater its influence, and, therefore, changes in the magma with time are more definite.

Thus, all the geological processes on the margin combine to create an original lithosphere, the combined rock material of which is similar to that of arc magma. The magma of ensimatic arcs is more similar to the final product of this evolution than that of ensialic arcs.

Conclusions

The method presented in this paper allows an understanding of the interaction between the various geological processes and thus helps in the study of the dynamics and evolution of active margins. By using this method on the Northwest Pacific margin the following may be concluded:

(1) The subduction zone–island arc–back-arc basin complex comprises a system with a variety of states. The states change both in space and in time and differ in the number and orientation of the associated echelons. One of the major "functions" of the system is the release of plate tectonic stress by subduction. The activity of the system is controlled by its state and the environment of subduction. Changes in state are caused by blocking, i.e. hindering, subduction. The lithosphere of the back-arc basins may be subducted by certain states of the system. New rock material generated by the system accumulates in the most stable parts, specifically in the island arcs and perhaps the continental margins.

(2) All the geological processes on the margin combine to create an original lithosphere, a major component of which is the arc magmatic products. The magma of the recent ensimatic arcs is more similar to the final product of this evolution at its present "island arc" stage, because the influence of the parental lithosphere is weaker here than in the ensialic complexes.

Thus, the active margin is a very dynamic system which cannot be destroyed even by severe collision between its arcs and thick, rigid blocks of oceanic or back-arc lithosphere. Until a thin, plastic lithosphere exists within or adjacent to the system (in the back-arc basins or in the ocean), i.e. until there are opportunities for subduction to take place the active margin cannot be destroyed—only changes in its structure or orientation may occur. However, if continent–continent collision should occur (Wilson, 1986) everything may change, and obviously diverse metamorphic processes would dominate in this case. Only a study of continental palaeogeosynclines can provide the answer to the question of what the final product of such an evolution would be. The method presented in this paper may well have a bearing on this.

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