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Paleogeography of Miocene Western Amazonia: Isotopic composition of molluscan shells constrains the influence of marine incursions

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ABSTRACT

Strontium, oxygen, and carbon isotope compositions of well-preserved mollusks (bivalves) indicate a dominantly freshwater depositional setting for the lower Miocene–upper Miocene Pebas Formation in Western Amazonia. Molluscan $^{87}Sr/^{86}Sr$ ratios identify different freshwater sources. Andean runoff was the dominant water source in Miocene Western Amazonia, though there was occasional influx of waters from cratonic catchments.

At only one stratigraphic level, isotope signals indicate increased (mesohaline) aquatic salinities, in concert with a clearly more saline molluscan faunal assemblage.

Strontium isotope–based salinity estimates are surprisingly low when compared to other paleosalinity estimates based on the interpretation of (ichno)faunal assemblages and sedimentological structures. We propose that these seemingly contrasting observations can be unified if Miocene Western Amazonia was occupied by a long-lived (lacustrine) wetland system with a restricted connection, via the Los Llanos Basin, to the Caribbean Sea. Abundant runoff supplied fresh water to this system, which effectively blocked the influx of saline waters through the restricted marine connection to the north. Much like modern Lake Maracaibo, such a system could have been the site of microtidal currents and thus could have hosted brackish-water fauna in a dominantly freshwater depositional system.

Keywords: Miocene, Amazonas, paleosalinity, paleohydrology, isotope geochemistry.

INTRODUCTION

In lowland Western Amazonia, fossiliferous Miocene deposits occur in outcrops and in the subsurface of Brazil, Colombia, and Peru. These strata, commonly grouped in the Pebas Formation (Peru) or Solimões Formation (Brazil), are distributed over many thousands of square kilometers in Western Amazonia (Fig. 1; e.g., Nuttall, 1990; Hoorn, 1993, 1994a; Räsänen et al., 1998). Pebas Formation sediments are commonly made up of an alternation of unconsolidated (smectitic) clays, silts, and sands, with intercalated lignites.

Hoorn (1994a) provided a (palyno)stratigraphic framework for the Pebas Formation (Fig. 2), placing the Pebas Formation outcrop groups, treated in the present paper, in the late early Miocene–early late Miocene interval (ca. 19–9 Ma).

In recent years, the depositional environment of the Pebas Formation has become a matter of some controversy. On the basis of detailed palynological analyses, complemented with sedimentological studies, Hoorn (1993, 1994a) concluded that Pebas Formation sequences were deposited in a fluviolacustrine environment, not unlike the modern flood plains of Amazonia. She further suggested episodic marine influences, mainly based on the occurrence of marine palynomorphs, as well as on the identification of *Thalassinoides*-type ichnofossils.

Ecological analyses of fossil bivalves and gastropods from the Pebas Formation (Wes-

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GSA Bulletin; August 2003; v. 115; no. 8; p. 983–993; 7 figures; 3 tables.

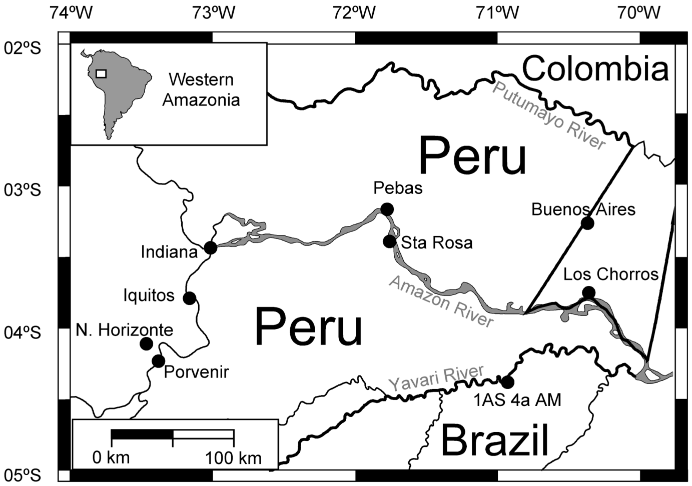

Figure 1. Map of the study area with outcrop and drill-core locations indicated.

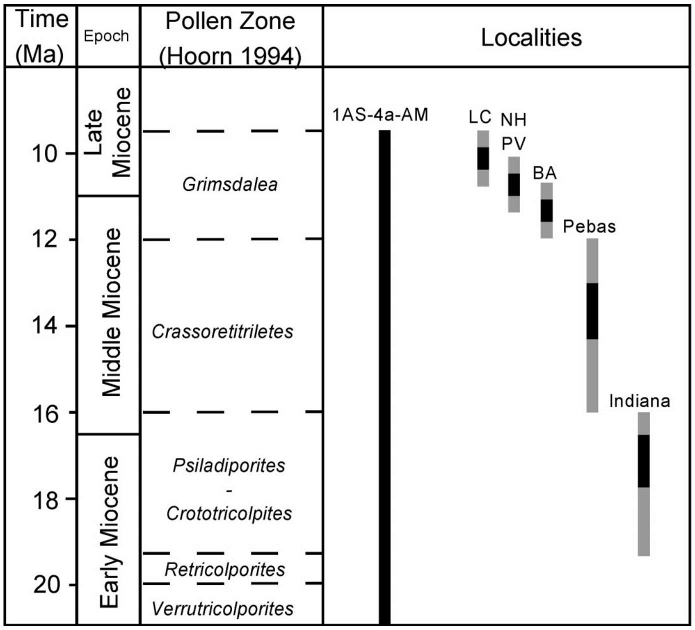

Figure 2. Stratigraphic ranges of Pebas Formation outcrops and core 1AS–4a-AM. Gray bars represent palynologic stratigraphic ranges (Hoorn, 1994b). Smaller ranges indicated by black bars are based on molluscan zonations of F. Wesselingh. LC—Los Chorros, NH and PV—Nuevo Horizonte and Porvenir, and BA—Buenos Aires. The time scale is that of Berggren et al. (1995).

selingh et al., 2002) support dominantly freshwater conditions, but point toward a shallow-water lacustrine environment rather than a flood plain environment. Consistent with palynological data, some molluscan taxa suggest a marine influence in the Pebas system (Nuttall, 1990; Wesselingh et al., 2002). Isotope studies of these mollusks by Vonhof et al. (1998) supported dominantly freshwater conditions and suggested an oligohaline setting for mollusks from a single outcrop in Buenos Aires, Colombia (Fig. 1). A distinctly more marine setting for the Pebas Formation was postulated by Räsänen et al. (1995), who reported tidal deposits in Acre, Brazil, that are possibly time equivalent to the youngest Peruvian Pebas Formation deposits. Therefore, it was suggested that a relatively open marine connection to Western Amazonia must have existed in the late Miocene.

Although differences in interpretation are evident, compiled data enable us to exclude some extreme scenarios. On the basis of general paleontology of the Pebas Formation, a fully marine depositional setting can be excluded. Common marine taxa are absent, and the bulk of Pebas fauna is endemic to Western Amazonia. Therefore, the proposed marine seaway across the South American continent in the middle Miocene (Webb, 1995) is not supported by existing paleontological data. On the other hand, there is good evidence that the Pebas system was not strictly a freshwater environment. For example, a number of Pebas taxa (fishes, gastropods) have modern relatives exclusively known from brackish-marine environments (Monsch, 1998; Vonhof et al., 1998). Also, frequent occurrence of *Thalassinoides* and other trace fossils as well as the (rare) occurrence of shark teeth, marine palynomorphs, and euryhaline benthic foraminifers point toward some kind of marine influence in the Pebas system.

With the present study we aim to refine Pebas Formation paleoenvironmental reconstructions by using the (isotope) chemical composition of well-preserved mollusks (bivalves). Expanding on the (pilot) study by Vonhof et al. (1998), we analyzed $^{87}Sr/^{86}Sr$ ratios, $\delta^{18}O$ and $\delta^{13}C$ values, and minor element concentrations of fossil mollusks over a wide stratigraphic range in the Pebas Formation. On the basis of these geochemical data we present new paleoenvironmental reconstructions and quantify paleosalinity ranges for the Pebas Formation.

MATERIAL AND METHODS

Samples were collected during our 1998 field campaign in Peru and Colombia. Additional material came from different sample collections (collections of A. Ranzi at the Universidade Federale do Acre, Rio Branco, Brazil; F.P. Wesselingh at the National Natuurhistorisch Museum, Leiden, Netherlands; and C. Hoorn, formerly at the Hugo de Vries Laboratory, Amsterdam, Netherlands).

Prior to $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$, and trace element analyses, handpicked and species-identified fossils and fossil fragments were briefly treated with ~3% HCl to remove surface contamination. For Sr isotope analyses, 1–5 mg of powdered shell was dissolved, and Sr was separated with "Elchrom Sr spec" ion-exchange resin. $^{87}Sr/^{86}Sr$ ratios were analyzed on a Finnigan MAT 261 or MAT 262 mass spectrometer, running a triple-jump routine, applying exponential fractionation correction, and normalizing to $^{86}Sr/^{88}Sr$ = 0.1194. All $^{87}Sr/^{86}Sr$ ratios are reported in Table 1, recalculated to a value of 0.710275 for the rou-

TABLE 1. MOLLUSCAN GEOCHEMICAL DATA

Locality	Height in section (m)	Sample number	Species	^{87}Sr/^{86}Sr	2 std. error	δ^{13}C (V-PDB) (‰)	δ^{18}O (V-PDB) (‰)	Fe (ppm)	Mn (ppm)	Sr (ppm)
Indiana group										
Indiana VI	26.0	F350	*Pachydon obliquus*	0.707767	0.000005	−10.29	−9.77	44	<40	1259
Indiana VI	21.0	F346	*Pachydon obliquus*	0.707871	0.000005	−7.09	−7.44	1653	59	1773
Indiana VI	19.0	F347	*Pachydon obliquus*	0.707900	0.000007	−9.24	−7.93	52	<40	993
Indiana VI	15.0	F348	*Pachydon obliquus*	0.707983	0.000006	−6.28	−4.95	54	<40	1474
Indiana VI	14.5	F349	*Pachydon obliquus*	0.707894	0.000006	−4.93	−7.27	52	<40	1340
Sta. Teresa I	9.5	F328	*Pachydon obliquus*	0.707894	0.000005	−9.12	−7.40	67	<40	1390
Indiana IV	9.5	F681	*Pachydon obliquus*	0.707879	0.000006	−8.87	−8.64	52	<40	1297
Sta. Teresa I	3.6	98RK10	*Pachydon obliquus*	0.707874	0.000007	−6.92	−6.33	33	<40	1454
Sta. Teresa I	2.0	F648	*Pachydon obliquus*	0.707913	0.000005	−7.53	−6.15	47	<40	1256
Sta. Teresa II	−0.5	F322	*Pachydon obliquus*	0.707924	0.000006	−6.56	−6.92	43	<40	1583
Sta. Teresa II	−1.0	F321	*Pachydon obliquus*	0.707883	0.000006	−6.90	−6.37	288	159	1665
Sta. Teresa II	−2.0	F320	*Pachydon obliquus*	0.707931	0.000005	−7.19	−7.24	22	<40	1372
Sta. Teresa II	−5.0	F318	*Pachydon obliquus*	0.707912	0.000007	−9.02	−9.40	52	<40	1288
Sta. Teresa IIa	−6.0	F323	*Pachydon obliquus*	0.709961	0.000005	−9.07	−7.10	97	164	1593
Sta. Teresa IIa	−6.0	F323	*Pachydon obliquus*	0.709469	0.000005	−8.23	−7.60	125	194	1765
Sta. Teresa IIa	−6.0	F323	*Pachydon obliquus*	0.708815	0.000006	−5.76	−5.06	106	42	1555
Sta. Teresa IIa	−7.0	F324	*Pachydon obliquus*	0.708028	0.000006	−6.63	−7.02	113	<40	1804
Pebas group										
Pijuayal II	0.7	F427	*Pachydon obliquus*	0.708063	0.000009	−9.41	−7.82	75	<40	1278
Pijuayal IV	0.7	F435	*Pachydon obliquus*	0.707858	0.000009	−8.65	−8.34	96	<40	1273
Pijuayal II	1.5	F428	*Pachydon obliquus*	0.707999	0.000008	−7.55	−7.46	104	<40	1099
Santa Julia V	11	F424	*Pachydon obliquus*	0.707795	0.000009	−7.87	−7.01	116	<40	1853
Santa Julia II	11	F588	*Pachydon obliquus*	0.707844	0.000008	−7.50	−7.46	110	<40	1774
Santa Julia	17.7	F94	*Pachydon obliquus*	0.707763	0.000010	−8.26	−8.45	137	46	1786
Santa Julia	26	F95	*Pachydon obliquus*	0.707978	0.000009	−8.99	−6.13	110	41	1745
Santa Julia VI	29	F422	*Pachydon obliquus*	0.707931	0.000009	−9.32	−6.49	80	<40	1172
Santa Julia	29	F96	*Pachydon obliquus*	0.707876	0.000008	−8.10	−8.20	237	<40	1679
Santa Julia	29.5	F629	*Pachydon obliquus*	0.707940	0.000008	−4.20	−6.18	90	71	1733
Santa Julia	32.5	F97/F631	*Pachydon obliquus*	0.707942	0.000009	−4.46	−2.96	120	41	1833
Santa Rosa	—	F538#1-1	*Pachydon tenuis*	0.707924	0.000009	−4.97	−4.86	163	<40	1551
Santa Rosa	—	F538#1-11	*Dyris lintea*	0.707862	0.000008	−5.20	−1.79	387	84	1645
Los Chorros group										
Los Chorros	0.00	1	*Pachydon obliquus*	0.708113	0.000006	−9.64	−7.74	66	<40	1650
Los Chorros	0.75	3	*Pachydon trigonalis*	0.708125	0.000033	−9.46	−7.67	n.a.	n.a.	n.a.
Los Chorros	1.75	5	*Pachydon* sp.	0.708314	0.000008	−11.65	−7.19	80	<40	926
Los Chorros	2.85	8	*Pachydon trigonalis*	0.708351	0.000005	−9.26	−5.21	53	51	1190
Los Chorros	4.25	11	*Pachydon trigonalis*	0.708121	0.000006	−9.91	−7.60	47	<40	1866
Los Chorros	7.00	16	*Pachydon cf. trigonalis*	0.708165	0.000009	n.a.	n.a.	n.a.	n.a.	n.a.
Los Chorros	7.25	19	*cf. Ampullaria* sp.	0.708548	0.000012	−9.10	−6.29	298	132	1359
Los Chorros	8.25	18	Indet. Mollusca	0.708408	0.000029	−9.51	−5.97	1606	83	621
Los Chorros	9.00	21a	*Pachydon trigonalis*	0.708377	0.000006	−6.73	−4.89	192	<40	1033
Los Chorros	9.00	21b	*Pachydon cf. acreanum*	0.708449	0.000006	−6.91	−4.58	275	49	759
Los Chorros	9.25	22a	*Pachydon carinatus*	0.708328	0.000006	−8.78	−7.02	95	<40	847
Los Chorros	9.25	22b	*Pachydon trigonalis*	0.708272	0.000018	−8.17	−8.36	110	46	788
Los Chorros	10.00	23a	*Pachydon tenuis*	0.708194	0.000006	−9.16	−9.05	67	<40	811
Los Chorros	10.50	24b	*Pachydon* sp.	0.708234	0.000005	−10.09	−10.06	104	55	592
Los Chorros	11.00	25	*Pachydon erectus*	0.708266	0.000007	−9.30	−8.21	130	87	850
Los Chorros	15.30	33	*Pachydon trigonalis*	0.708369	0.000010	n.a.	n.a.	n.a.	n.a.	n.a.
Los Chorros	15.70	33a	*Pachydon trigonalis*	0.708387	0.000007	−7.40	−3.73	90	<40	921
Los Chorros	17.25	35	*Pachydon trigonalis*	0.708195	0.000008	−9.83	−8.19	102	<40	1105
Los Chorros	27.25	50	Indet. Mollusca	n.a.	n.a.	−6.33	−1.23	n.a.	n.a.	n.a.
Los Chorros	31.25	54	Indet. Mollusca	0.708456	0.000008	n.a.	n.a.	n.a.	n.a.	n.a.
Los Chorros	31.75	55	*Pachydon trigonalis*	0.708526	0.000006	−7.01	−3.54	125	<40	1065
Los Chorros	32.00	56a	*Pachydon trigonalis*	0.708610	0.000006	−5.95	−3.47	312	<40	716
Los Chorros	32.00	56b	*Aylacostoma browni*	0.708522	0.000006	−4.00	0.34	810	<40	1367
Los Chorros	32.50	57	Indet. Mollusca	0.708499	0.000026	n.a.	n.a.	n.a.	n.a.	n.a.
Los Chorros	35.00	58a	*Pachydon trigonalis*	0.708302	0.000020	−8.89	−8.00	76	<40	459
Los Chorros	35.00	58a	*Pachydon trigonalis*	0.708338	0.000010	−8.89	−8.00	76	<40	459
Los Chorros	35.00	58b	*Toxosoma* sp.	0.708276	0.000029	−8.29	−7.26	314	<40	847
Porvenir group										
Porvenir	5.5	F715	*Pachydon obliquus*	0.708035	0.000009	−10.42	−6.32	334	<40	1053
Porvenir	5.5	F715	*Corbicula* sp.	0.708185	0.000007	−10.48	−4.46	72	<40	1477
Porvenir	5.5	F715	*Melongena woodwardi*	0.708468	0.000007	−9.85	−3.53	100	46	2527
Porvenir	6.3	F717b	*Melongena woodwardi*	0.708250	0.000006	−8.46	−3.31	257	41	3167
Porvenir	6.3	F717b	*Pachydon carinatus*	0.708008	0.000009	−10.62	−4.82	1380	<40	2025
Porvenir	5.5	F727-1	*Melongena woodwardi*	0.708236	0.000005	−9.86	−3.13	155	69	2538
Porvenir	5.5	F727-2	*Melongena woodwardi*	0.708312	0.000008	−8.86	−2.33	137	68	2534
Porvenir	5.5	F727-3	*Melongena woodwardi*	0.708354	0.000006	−8.51	−2.53	132	83	2488
Porvenir	5.5	F727-4	*Melongena woodwardi*	0.708342	0.000007	−8.52	−2.10	128	88	2547
Nuevo Horizonte	—	F70	*Odostomia* sp.	0.708305	0.000007	−8.72	−5.49	n.a.	n.a.	n.a.
Nuevo Horizonte	—	F70	*Corbicula* sp.	0.708294	0.000008	−9.71	−5.53	n.a.	n.a.	n.a.
Nuevo Horizonte	—	F70	*Pachydon obliquus*	0.708289	0.000007	−10.56	−2.11	<40	<40	1067
Nuevo Horizonte	—	F70	*Ammonia/Elphidium* sp.	0.708617	0.000009	−11.42	−4.29	n.a.	n.a.	n.a.

(*Continued*)

TABLE 1. (*Continued*)

Locality	Height in section (m)	Sample number	Species	^{87}Sr/^{86}Sr	2 std. error	δ^{13}C (V-PDB) (‰)	δ^{18}O (V-PDB) (‰)	Fe (ppm)	Mn (ppm)	Sr (ppm)
Nuevo Horizonte	—	F70 (FP1)	*Melongena woodwardi*	0.708424	0.000010	−9.16	−0.34	66	137	2413
Nuevo Horizonte	—	F 367a	*Corbicula* sp.	0.708485	0.000009	−11.41	−1.54	62	100	1688
Nuevo Horizonte	—	F 367a	*Pachydon obliquus*	0.708134	0.000006	−8.29	−6.45	<40	<40	846
Buenos Aires outcrop										
Buenos Aires	—	F46	*Panamicorbula* sp.	0.708996	0.000007	0.62	−2.71	107	69	2877
Buenos Aires	—	F46	*Balanus* sp.	0.708894	0.000009	−3.91	−3.98	n.a.	n.a.	n.a.
Buenos Aires	—	F49c	*Balanus* sp.	0.708914	0.000005	−0.67	−5.06	4977	4290	1384
Buenos Aires	—	F49c	*Panamicorbula* sp.	0.708975	0.000009	−4.72	−3.59	50	<40	2790
Buenos Aires	—	F49c	*Nassarius reductus*	0.709000	0.000009	−2.72	−3.54	100	142	3422
Buenos Aires	—	no nr-1	*Melongena woodwardi*	0.709013	0.000008	−0.18	−4.06	1350	311	5074
Buenos Aires	—	no nr-2	*Melongena woodwardi*	0.709015	0.000009	0.47	−3.72	1072	390	4929
Buenos Aires	—	no nr-3	*Melongena woodwardi*	0.709015	0.000008	0.16	−4.00	890	227	4832
Buenos Aires	—	no nr	*Panamicorbula* sp.	0.709025	0.000008	−3.69	−3.46	70	42	2447
Buenos Aires	—	C52-1	*Dyris* sp.	0.709026	0.000009	−3.95	−4.32	150	75	2093
CPRM 1AS 4a AM										
1AS-4a-AM	23.00		*Pachydon cf. tenuis*	0.708082	0.000006	−10.58	−8.86	61	50	1004
1AS-4a-AM	28.00		*Pachydon cuneatus*	0.708020	0.000006	−9.89	−5.38	47	40	984
1AS-4a-AM	32.40		*Pachydon erectus*	0.708199	0.000008	−9.62	−4.95	74	<40	1814
1AS-4a-AM	37.00		*Pachydon obliquus*	0.708154	0.000006	−8.85	−4.91	<40	<40	1393
1AS-4a-AM	49.40		*Pachydon obliquus*	0.708216	0.000007	−8.49	−7.26	45	<40	1337
1AS-4a-AM	59.20		*Pachydon obliquus*	0.708338	0.000007	−7.28	−3.73	41	<40	1511
1AS-4a-AM	65.75		*Pachydon obliquus*	0.708241	0.000006	−10.64	−5.73	79	<40	1784
1AS-4a-AM	77.50		*Pachydon obliquus*	0.708199	0.000006	−7.15	−7.47	48	<40	1176
1AS-4a-AM	80.15		*Pachydon obliquus*	0.708649	0.000008	−6.98	−4.88	48	<40	996
1AS-4a-AM	84.20		*Pachydon cf. tenuis*	0.708851	0.000007	−12.01	−5.99	139	<40	1137
1AS-4a-AM	85.20		*Pachydon obliquus*	0.709299	0.000009	−9.49	−5.63	55	<40	945
1AS-4a-AM	95.60		*Pachydon obliquus*	0.709022	0.000006	−7.43	−4.58	<40	<40	1303
1AS-4a-AM	117.30		Mollusca indet.	0.708815	0.000008	−11.82	−8.70	112	46	1134
1AS-4a-AM	130.55		*Pachydon obliquus*	0.709736	0.000007	−8.15	−7.67	59	<40	1461
1AS-4a-AM	134.70		*Pachydon* sp.	0.709250	0.000008	−8.84	−6.35	101	<40	940
1AS-4a-AM	150.75		*Pachydon obliquus*	0.708279	0.000007	−5.22	−6.42	113	<40	1520
1AS-4a-AM	162.20		*Pachydon carinatus*	0.708339	0.000007	−7.44	−4.36	<40	<40	1643
1AS-4a-AM	210.65		*Pachydon* sp.	0.708078	0.000007	−11.93	−6.23	<40	<40	1438
1AS-4a-AM	247.00		*Pachydon* sp.	0.708158	0.000006	−10.76	−4.37	92	51	1990
1AS-4a-AM	296.45		*Pachydon* sp.	0.708324	0.000007	−7.12	−5.24	157	45	1301
1AS-4a-AM	300.20		*gastrop.* Indet.	0.709137	0.000008	−8.55	−8.47	104	<40	1646
1AS-4a-AM	312.30		*Pachydon obliquus*	0.707993	0.000005	−8.87	−4.50	<40	<40	1649

Note: Chemical data of all Pebas Formation samples analyzed, listed by outcrop group. All samples with Fe concentrations higher than 200 ppm or Mn concentrations higher than 100 ppm are considered to be diagenetically altered. n.a.—not analyzed, <40 indicates that the value was below the 40 ppm detection limit for the ICP-AES analyses.

tinely analyzed NBS 987 standard. Long-term NBS 987 reproducibility was better than 0.000015 (2σ) on both machines used. Sr blanks were <0.01% of the total Sr concentration in the samples.

Carbon and oxygen isotope data from a 20–80 μg split of the same sample powders were run on a Finnigan MAT 252 mass spectrometer, equipped with an automated carbonate extraction line. Samples were digested in concentrated orthophosphoric acid at 80 °C. A routinely analyzed carbonate standard was reproducible within 0.09‰ for δ^{18}O and 0.05‰ for δ^{13}C (1σ). Both δ^{18}O and δ^{13}C data are reported relative to the Vienna–Peedee belemnite (V-PDB) standard.

Minor element analyses were performed on a Varian Liberty ICP-AES (inductively coupled plasma–atomic-emission spectrometer) after digestion of ~1.5 mg of powdered sample in 1 *N* HNO_3 and subsequent dilution to an ~0.1 *N* HNO_3 sample solution. Concentrations of Fe, Mn, and Sr are reported in parts per million (ppm). Conservative ICP-AES detection limits are set at 40 ppm for both Mn and Fe. A standard test experiment indicated a reproducibility (1σ) of better than 5% for the method used.

The geologic time scale used in this paper is that of Berggren et al. (1995). Salinity is reported in practical salinity units (psu), which is equivalent to the per mil (‰) salinity notation. We further follow the "Venice 1958" salinity scale for descriptive salinity ranges. Four ranges are of interest for the sequences under study: 0–0.5 psu for fresh water, 0.5–5 psu for oligohaline water, 5–18 psu for mesohaline water, and 18–30 psu for polyhaline water.

DIAGENETIC EVALUATION

All molluscan species analyzed were found to be aragonitic (by Raman microspectrometry; see Burke [2001] for methodology). SEM (scanning electron microscope) images of representative specimens of each outcrop group showed the original mineralogy of the mollusks under study (dominantly crossed lamellar structures). No diagenetic encrustations or infillings were detected. Perhaps the strongest evidence for the pristine preservation of shells from these outcrops is the existence of seasonal δ^{18}O cyclicity in their growth increments, comparable to that of modern shells from Western Amazonia (Vonhof et al., 1999; Kaandorp et al., 2000).

To evaluate diagenetic alteration of each of the samples analyzed, we have checked for elevated concentrations of Mn and Fe, which are commonly taken to indicate diagenetic alteration (e.g., Veizer, 1983; Jones et al., 1994; McArthur, 1994). For the present study, we have set threshold values for chemically well-preserved mollusks at 200 ppm for Fe and 100 ppm for Mn. Samples with higher Fe or Mn concentrations have been excluded from the salinity calculations in this paper.

OUTCROP DESCRIPTIONS

During our 1998 field campaign, we visited three outcrop groups along the Amazon River

TABLE 2. END MEMBERS FOR SALINITY CALCULATIONS

End member	$^{87}Sr/^{86}Sr$	Sr (mM/kg)	(Sr ppm)
Seawater *Grimsdalea* zone	0.708867	90	7.886
Seawater *Crassoretitriletes* zone	0.708767	90	7.886
Seawater *Psiladiporites* zone	0.708550	90	7.886
Cratonic fresh water	0.7282	0.122	0.0107
Andean fresh water	0.7074	0.475	0.0416
Napo River	0.7059	0.475	0.0416

Note: Marine Sr isotope values for the different middle to late Miocene pollen zones taken from Howarth and McArthur (1997). In combination with cratonic and Andean freshwater end members, these marine values are used to calculate paleosalinities based on Pebas Formation molluscan $^{87}Sr/^{86}Sr$ data.

TABLE 3. AMAZONIAN CATCHMENTS

Catchment	$^{87}Sr/^{86}Sr$	Sr (mM/kg)	Sr (ppm)
Andean catchments			
Madeira subbasin	0.7188	1.119	0.098
Ucayali-Maranon subbasin	0.7093	2.678	0.235
Northern Andes subbasin	0.7074	0.332	0.0291
Cratonic catchments			
Guyana craton rivers	0.7266	0.117	0.0103
Brazilian craton rivers	0.7307	0.128	0.0112

Note: Sr isotope values and Sr concentrations of modern Amazonian catchments after Palmer and Edmond (1992).

(Fig. 1). These were outcrops near the villages of Indiana (lat 3°30.1′S, long 73°02.5′W) and Pebas (lat 3°19.5′S, long 71°51.0′W) in Peru, as well as the Los Chorros outcrop group (lat 3°47.7′S, long 71°20.8′W) not far from the village of Puerto Nariño in Colombia. Outcrops are up to a few tens of meters high, and bedding is slightly inclined throughout the area. We further analyzed fossils from a Brazilian drill core (Brazilian Companhia de Pesquisas de Recursos Minerais [CPRM] core 1AS–4a-AM) through the Pebas Formation. Although fossil molluscan shells are common, in some stratigraphic intervals of core and outcrops, a continuous molluscan record of the Pebas Formation is not available. Mollusk-barren gaps of up to 15 m thickness occur in several of the successions studied.

ISOTOPE-BASED PALEOSALINITY CALCULATIONS

Both $^{87}Sr/^{86}Sr$ ratios and $\delta^{18}O$ values have previously been used to determine the aquatic salinities of modern and ancient brackish-water systems (Eisma et al., 1976; Ingram and DePaolo, 1993; Bryant et al., 1995; Holmden et al., 1997; Spencer and Patchett, 1997; Vonhof et al., 1998). For the Pebas Formation, accurate $\delta^{18}O$- and $\delta^{13}C$-based salinity reconstructions are hampered by significant (seasonal) variability in $\delta^{18}O$ and $\delta^{13}C$ values of Amazonian fresh water. Seasonal variations of >6‰ in the $\delta^{18}O$ and $\delta^{13}C$ values in growth increments of single specimens of modern and fossil Amazonian freshwater bivalves have been observed (Vonhof et al., 1999; Kaandorp et al., 2000).

In contrast, $^{87}Sr/^{86}Sr$ ratios of molluscan aragonite are not influenced by evaporation-precipitation balance changes or by biological fractionation. Therefore, a simple binary-mixing model applied to molluscan $^{87}Sr/^{86}Sr$ ratios yields robust paleosalinity estimates for the Pebas Formation (Vonhof et al., 1998). Because seawater has an ~100–1000 times higher Sr concentration than most freshwater sources (Palmer and Edmond, 1989), salinity calculations based on $^{87}Sr/^{86}Sr$ ratios are particularly sensitive in the lower-salinity reaches (0–10 psu salinity) and decrease dramatically in resolution for higher-salinity water masses (e.g., Ingram and DePaolo, 1993; Bryant et al., 1995; Holmden et al., 1997; Vonhof et al., 1998).

Following Vonhof et al. (1998) we applied a standard binary-mixing model for the calculation of Miocene Western Amazonian aquatic salinities (equation 1) using three isotopically distinct end members for the mixing calculation: (1) Miocene seawater, (2) cratonic runoff, and (3) Andean runoff. In the present paper, we will apply the same three end members, with a few modifications outlined subsequently.

$$
\begin{aligned}
{}^{87}Sr/{}^{86}Sr_m = \{ & ({}^{87}Sr/{}^{86}Sr_a \times [Sr]_a \times A \\
& + {}^{87}Sr/{}^{86}Sr_b \times [Sr]_b \times B)\} \\
& \div \{(A \times [Sr]_a + B \times [Sr]_b)\}, \quad (1)
\end{aligned}
$$

where $^{87}Sr/^{86}Sr_m$ is the Sr isotope ratio of the mixture, $^{87}Sr/^{86}Sr_a$ and $^{87}Sr/^{86}Sr_b$ are the Sr isotope ratios of each of the end members, $[Sr]_a$ and $[Sr]_b$ are the Sr concentrations of each of the end members, and A and B are the relative proportions of each end member in the mixture ($A + B = 1$).

Miocene Seawater

The Miocene seawater $^{87}Sr/^{86}Sr$ composition is well documented. A compilation by Howarth and McArthur (1997) provides reliable seawater $^{87}Sr/^{86}Sr$ ratios for the complete Cenozoic Era. Because seawater $^{87}Sr/^{86}Sr$ ratios increased steadily through the Miocene, different values for seawater $^{87}Sr/^{86}Sr$ are implemented in the binary-mixing model for each Pebas Formation palynostratigraphic zone (Table 2). The well-documented conservative behavior of dissolved Sr in the oceans allows for modern marine Sr concentrations (~90 μmol/kg; Palmer and Edmond, 1989) to be applied for Miocene oceans as well.

Cratonic Fresh Water

Modern Amazonian catchments draining old crustal rock on the Brazilian and Guyana cratons feed rivers with the highest $^{87}Sr/^{86}Sr$ ratios of the Amazon Basin (Palmer and Edmond, 1992). Tectonically quiescent cratonic hinterlands have supposedly not changed much since the Miocene. Therefore we apply an average modern cratonic river $^{87}Sr/^{86}Sr$ value of 0.7282 (Table 2) for our Miocene end member without modifications.

Andean Fresh Water

Palmer and Edmond (1992) analyzed modern Amazon River headwaters that are produced in three Andean subbasins. They found that rivers in the Northern Andes subbasin (Table 3; Fig. 3), dominantly draining weathered andesites, yield the lowest $^{87}Sr/^{86}Sr$ values of the Amazon Basin. Although Andean hinterlands have remained tectonically active since the Miocene (e.g., Hoorn et al., 1995; Lundberg et al., 1998), it is unlikely that riverine $^{87}Sr/^{86}Sr$ values lower than those from the Northern Andes subbasin have ever been common in Andean catchments.

For the Andean end member we have chosen the average $^{87}Sr/^{86}Sr$ value of 0.7074 of three larger rivers in this northern subbasin coupled with the (highest) Sr concentration of the Napo River (Palmer and Edmond, 1992; Table 2). This Miocene Andean freshwater end member has a distinctly lower $^{87}Sr/^{86}Sr$ ratio than average Andean runoff, presumably

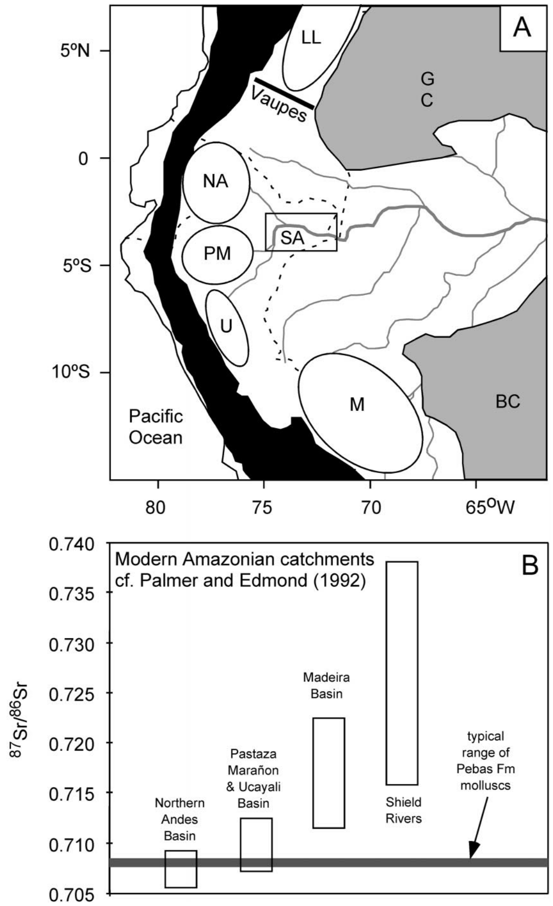

Figure 3. (A) Map of Western Amazonia, with different subbasins as defined by Palmer and Edmond (1992) schematically indicated. NA—Northern Andes subbasin, M—Madeira subbasin. The Ucayali-Marañon subbasin is here further subdivided into the Pastaza-Marañon (PM) subbasin and Ucayali (U) subbasin. The Los Llanos Basin (LL) is separated from Western Amazonia by the Vaupes structural arch. Modern river patterns are indicated in gray; international boundaries are marked with broken lines. The Guyana craton (GC) and Brazilian craton (BC) are shown as gray areas, and the Andes mountain range is in black. Core and outcrops of the present study come from the rectangle marked SA (study area; enlarged in Fig. 1). (B) Modern riverine $^{87}Sr/^{86}Sr$ ranges of the Amazonian subbasins (cf. Palmer and Edmond, 1992).

causing equation 1 to yield overestimated (rather than underestimated) salinities of seawater + Andean freshwater mixtures.

RESULTS

Strontium Isotope Salinity Calculations

The Indiana Outcrop Group

This outcrop group, of Burdigalian–Langhian age (ca. 19–16 Ma; *Psiladiporites-Crototricolpites* pollen zone of Hoorn [1994b]), generally yields relatively low Sr isotope ratios (in a range between 0.7077 and 0.7080), which requires the contribution of a considerable share of Andean runoff (Fig. 4A). With the exception of one sample, molluscan $^{87}Sr/^{86}Sr$ ratios plot well beneath the 0.5 psu salinity line, calculated by using equation 1 with the end-member compositions of Andean fresh water and seawater from Table 2. The anomalous sample occurs at the −6 m level in the composite section. Repeated analyses of three different specimens of the bivalve *Pachydon obliquus* give scattered but consistently higher values (0.7088–0.7100) than contemporaneous seawater. Therefore, these $^{87}Sr/^{86}Sr$ ratios appear to indicate a considerable cratonic runoff contribution to the otherwise Andean-runoff–dominated host water.

The Pebas Outcrop Group

Hoorn (1994b) placed this outcrop group in the *Crassoretitriletes* pollen zone (Langhian–Serravallian; ca. 16–12 Ma). Some data from the contemporaneous Santa Rosa de Pichana section (lat 3°40.04′S, long 71°45.58′W) have been added to the data table of the Pebas outcrop group (Table 1).

Pebas outcrop group mollusks come close to the Andean runoff end member (Fig. 4B), just like those from the Indiana outcrop group. All $^{87}Sr/^{86}Sr$ ratios fall in a narrow range (0.7078–0.7081), suggesting a relatively stable water chemistry. Calculated salinities (using equation 1 with end-member data from Table 2) are consistently <0.5 psu (Fig. 4B).

The Buenos Aires Outcrop

This small outcrop is situated in Colombian Amazonia, on the banks of the Cotuhe River, near the border with Peru. Hoorn (1994b) showed the strata to belong to the same palynozone as Los Chorros and Porvenir (*Grimsdalea* zone; Serravallian–Tortonian). More refined molluscan zonations suggest that the Buenos Aires outcrop stratigraphically underlies Los Chorros and Porvenir. The Buenos Aires outcrop clearly stands out from the other outcrops in having a more marine signature in the palynomorphs and molluscan faunas (Hoorn, 1994b; Vonhof et al., 1998; Wesselingh et al., 2002).

Significant Fe and Mn enrichment in some specimens (*Nassarius* sp., *Melongena woodwardi*, *Balanus* sp.; Table 1) suggests that they are diagenetically altered. The remaining four well-preserved specimens define a narrow range of $^{87}Sr/^{86}Sr$ ratios between 0.708975 and 0.709026, slightly higher than contemporaneous seawater.

Equation 1 indicates that this narrow $^{87}Sr/^{86}Sr$ range represents oligohaline to mesohaline conditions for a cratonic freshwater + seawater mixture (Table 2). Because the resolution of $^{87}Sr/^{86}Sr$-derived paleosalinity calculations is considerably lower at these elevated salinities, small errors in the exact age (= end-member $^{87}Sr/^{86}Sr$ value) of the Buenos Aires strata can have a significant impact on the calculated salinity range.

The Porvenir and Nuevo Horizonte Outcrops

Slightly postdating the Buenos Aires outcrop, the Porvenir and Nuevo Horizonte successions represent *Grimsdalea* zone Pebas Formation deposits in the western part of our study area (Fig. 1). Molluscan $^{87}Sr/^{86}Sr$ values are in a range between 0.7081 and 0.7085. For a mixture of *Grimsdalea* zone seawater and Andean fresh water (Table 2), equation 1 indicates <0.5 psu salinity for most mollusk shell samples (all are <1 psu).

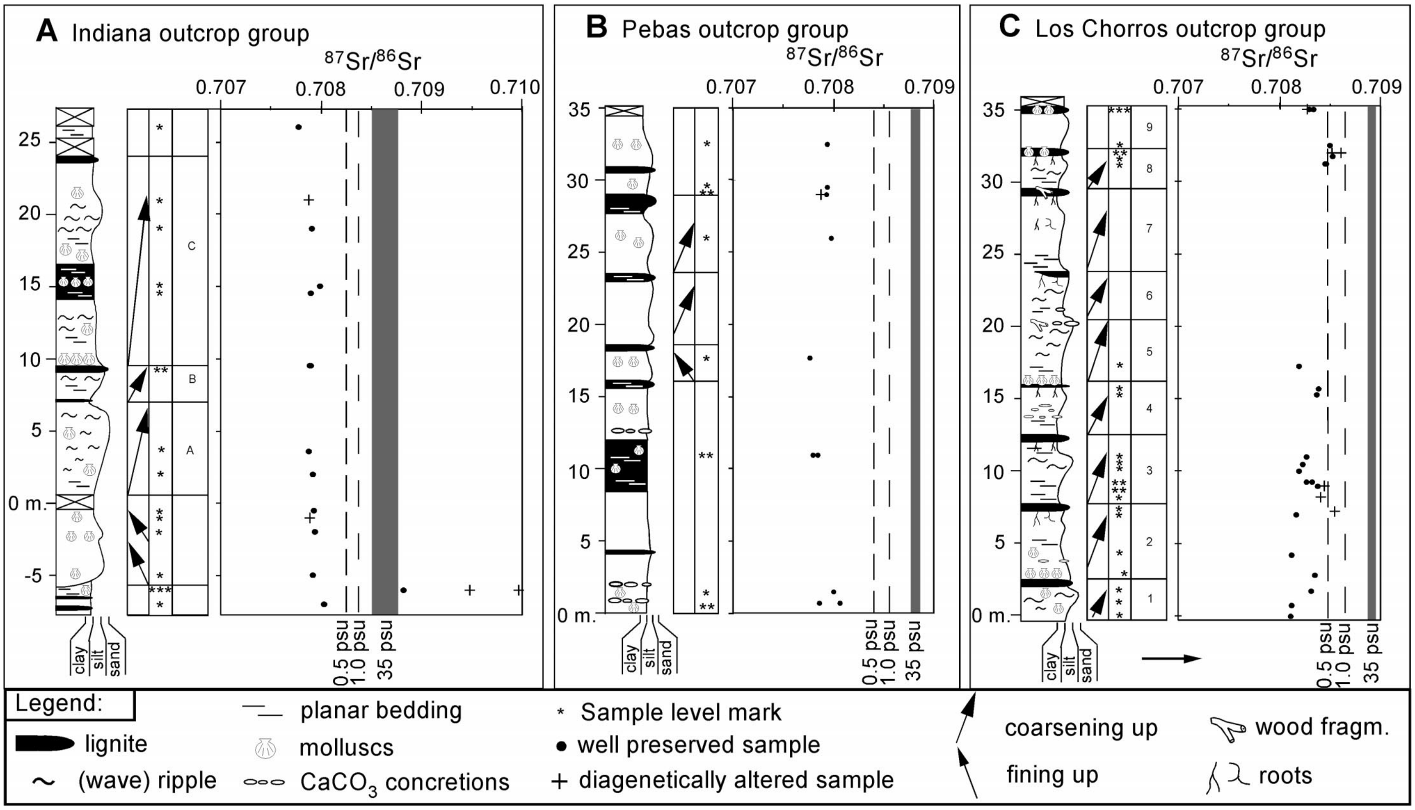

Figure 4. Schematic stratigraphic logs for three outcrop groups of the Pebas Formation. Seawater $^{87}Sr/^{86}Sr$ variation over the complete stratigraphic length of the corresponding pollen zone is indicated by vertical gray bars. Vertical broken lines indicate 0.5 and 1.0 psu salinity lines calculated with equation 1 and end-member data from Table 2. Sequences marked A, B, and C in A correspond to the sequences of Räsänen et al. (1998). Sequence numbers 1–9 in C refer to individual stacked coarsening-upward sequences in the Los Chorros outcrop group. All molluscan $^{87}Sr/^{86}Sr$ data are plotted. Mollusk shell samples with Fe concentrations of >200 ppm or Mn concentrations of >100 ppm are taken to be diagenetically altered; these are plotted with a separate plot symbol (+).

In a single level of the Nuevo Horizonte outcrop, small benthic foraminifera (*Ammonia* sp. and *Elphidium* sp.) are relatively abundant. These euryhaline genera are also known from some other Pebas Formation records (see Hoorn, 1994b). Nuevo Horizonte foraminifera are relatively poorly preserved. Many specimens show extensive recrystallization of foraminiferal calcite on SEM photographs, which is peculiar in view of the excellent preservation of molluscan aragonite in the same sample. Low values of foraminiferal $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ values (Table 1) indicate a freshwater to oligohaline environment for the foraminifera, which is within the low-salinity limit of modern *Elphidium* and *Ammonia* salinity-tolerance ranges. Given their poor preservation, however, one must take into account that their isotopic composition could have been diagenetically altered.

The Los Chorros Outcrop Group

Los Chorros is the youngest outcrop group we studied in the area. Belonging to the Serravallian–Tortonian *Grimsdalea* zone (ca. 12–9 Ma; Hoorn, 1994b), molluscan zonations suggest that the Los Chorros strata postdate outcrops at Buenos Aires and Porvenir (Fig. 2). Sedimentologically, the Los Chorros strata show very repetitive coarsening-upward cycles, each ~3–6 m thick (Fig. 4C). These cycles are capped by lignites, containing abundant plant and tree remains. Most lignites have root zones preserved underneath, which confirms the shallowing-upward signature of each coarsening-upward cycle. This Los Chorros sedimentary record is interpreted to represent a stack of at least eight prograding coastal sequences deposited in a lake or embayment.

$^{87}Sr/^{86}Sr$ values are in the same range as for Porvenir and Nuevo Horizonte (0.7080–0.7086; Fig. 4C), which is distinctly higher than the Pebas and Indiana outcrop groups. A clear correlation between $^{87}Sr/^{86}Sr$ ratios and the sedimentary cyclicity is not evident from the present data, which suggests that no significant salinity change took place through individual coarsening-upward cycles. Calculated salinities for well-preserved mollusks of the Los Chorros outcrop group, using equation 1 for a mixture of *Grimsdalea* zone seawater and Andean fresh water (Table 3), are all <0.5 psu for the lower five cycles. Closer to the top in cycle number 8, calculated salinities plot between 0.5 and 1.0 psu (Fig. 4C).

CPRM Core IAS-4a-AM

In the 1970s, an extensive drilling program was carried out by the Brazilian Companhia de Pesquisas de Recursos Minerais (CPRM) to study the lignitic intervals of the Solimões Formation (Maia et al., 1977). Continuous cores, taken during this program, are a valuable archive of Pebas (Solimões) Formation stratigraphy. Mollusks from CPRM core 1AS–4a-AM, already studied palynologically by Hoorn (1994b), were analyzed to obtain a $^{87}Sr/^{86}Sr$ record through the complete Pebas stratigraphy at a single location (Fig. 5).

In core interval 80–140 m, $^{87}Sr/^{86}Sr$ values are much higher (0.7086–0.7097) than in the rest of the palynologically dated core interval

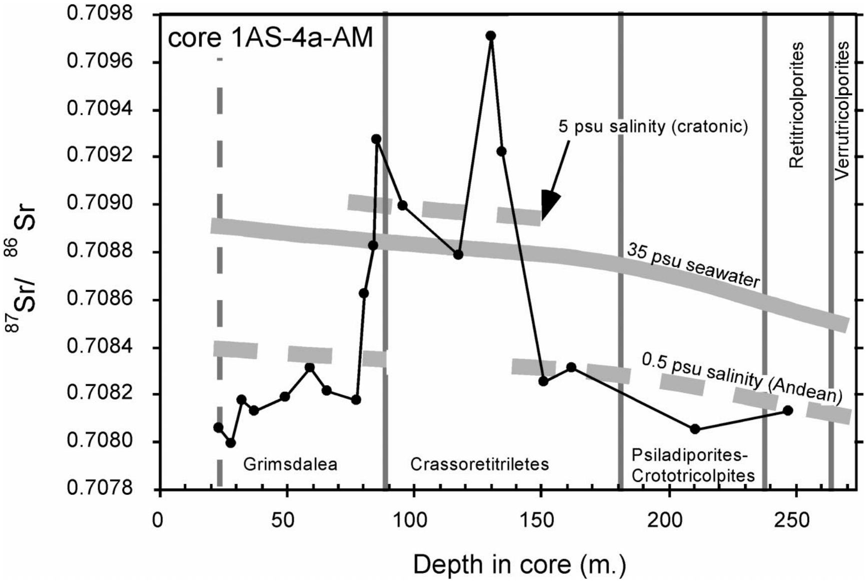

Figure 5. Molluscan ^{87}Sr/^{86}Sr data of CPRM core 1AS–4a-AM in the core interval between 20 and 270 m, with palynostratigraphic zonation by Hoorn (1994b) indicated. Seawater ^{87}Sr/^{86}Sr curve is taken from Howarth and McArthur (1997). Broken gray lines represent salinity zonations calculated with equation 1 using Andean and cratonic freshwater end-member data (from Tables 2 and 3). Note that core interval 80–140 m is interpreted to be dominated by an Andean + cratonic freshwater mixture (see text). The 5.0 psu salinity line drawn in that interval is meant to illustrate the less likely scenario of a seawater + cratonic freshwater mixture.

(0.7080–0.7083). Because ^{87}Sr/^{86}Sr ratios are well above contemporaneous seawater and only rarely come near the marine ^{87}Sr/^{86}Sr curve (Fig. 5), this ^{87}Sr/^{86}Sr pattern indicates a prolonged period of increased input of cratonic fresh water, rather than increased marine influence.

On the basis of a seawater + Andean freshwater mixture for the intervals with lower ^{87}Sr/^{86}Sr values—i.e., between 20 and 80 m and between 140 and 270 m—calculated paleosalinities represent freshwater conditions (Fig. 5).

δ^{18}O and δ^{13}C Values of Pebas Formation Mollusks

Molluscan δ^{18}O and δ^{13}C values occupy a wide range of >8‰ each. It makes no difference whether we consider all mollusk shell samples measured (Fig. 6A) or confine our data to the most common genus *Pachydon* (Fig. 6B). Within some outcrop groups (e.g., Indiana), positive correlations of δ^{18}O and δ^{13}C values can be observed. All data plotted together, however, show no clear trends. Observed depleted δ^{18}O and δ^{13}C values are atypical for marine environments. They do, however, overlap with δ^{18}O and δ^{13}C values of modern Amazonian freshwater mollusks (Vonhof et al., 1999; Kaandorp et al., 2000).

Most outcrop groups have considerable overlap in their stable isotope values. The main exception is Buenos Aires, which has comparatively high δ^{13}C values, interpreted to relate to the significant contribution of marine water inferred from the ^{87}Sr/^{86}Sr ratios.

DISCUSSION

Pebas Formation Paleosalinity Reconstructions

^{87}Sr/^{86}Sr ratios from Pebas Formation outcrop groups, plotted over their full palynostratigraphic range, are commonly much lower than contemporaneous seawater ^{87}Sr/^{86}Sr ratios (Fig. 7), indicating that the Pebas system was dominated by Andean fresh water. Superimposed in Figure 7A are the paleosalinity fields for this part of the Neogene, calculated with equation 1 using the marine ^{87}Sr/^{86}Sr reference curve for the Miocene (Howarth and McArthur, 1997). The Andean freshwater end member is fixed at a ^{87}Sr/^{86}Sr ratio of 0.7074 and a Sr concentration of 0.0416 μmol/L (Table 2). Resulting salinity fields in Figure 7A represent maximum-salinity estimates for two reasons:

1. Salinities are calculated on the basis of a binary mixture of Andean fresh water + seawater. In the triple end-member system at hand, addition of the third end member (cratonic fresh water) could only reduce the calculated salinity at any given ^{87}Sr/^{86}Sr value by increasing the ^{87}Sr/^{86}Sr value of the freshwater end member.

2. As discussed earlier in this paper, the Andean freshwater end-member composition (^{87}Sr/^{86}Sr = 0.7074 at 0.416 μmol/L) applied in Figure 7A represents only the Northern Andes subbasin as it has the lowest ^{87}Sr/^{86}Sr values. The presumable option of a Miocene Andean freshwater end member with higher ^{87}Sr/^{86}Sr values would decrease calculated salinities.

Much higher molluscan ^{87}Sr/^{86}Sr ratios are observed in the Buenos Aires outcrop. Here, molluscan ^{87}Sr/^{86}Sr ratios occupy a narrow range just above contemporaneous seawater ^{87}Sr/^{86}Sr ratios (Fig. 7A), which points toward a stable aquatic ^{87}Sr/^{86}Sr chemistry, typical of higher-salinity waters. Higher-than-seawater ^{87}Sr/^{86}Sr ratios indicate the influence of cratonic fresh water, as opposed to Andean fresh water, in the Buenos Aires samples. In these higher-salinity ranges, calculated salinity zonations based on molluscan ^{87}Sr/^{86}Sr values are less robust. Reasonable variation in the stratigraphic age or cratonic freshwater end-member composition can change our estimate from dominantly mesohaline to oligohaline or polyhaline.

Elevated salinities in the Buenos Aires outcrop are supported by various other observations: (1) exceptionally abundant paleontological indications for brackish water, such as mangrove pollen, euryhaline foraminifera (Hoorn, 1994b), and brackish-water mollusks (*Odostomia* spp., *Nassarius* sp., *Melongena woodwardi*, *Macoma* sp., *Panamicorbula* sp.; Wesselingh et al., 2002); (2) molluscan δ^{13}C values much closer to seawater values than at all other localities (Fig. 6A); and (3) two to five times higher molluscan Sr concentrations compared to other localities, which is interpreted to relate to the much higher Sr concentration in seawater (Table 1; cf. Vonhof et al., 1998). In particular, two well-preserved specimens of *Panamicorbula* sp. have much higher Sr concentrations than the closely related Pachydontinae from all other locations.

High ^{87}Sr/^{86}Sr ratios of mollusks from the Indiana outcrop group and from core 1AS–4a-AM (Table 1) are much more scattered and lack these additional indications for increased salinity. This finding supports our general

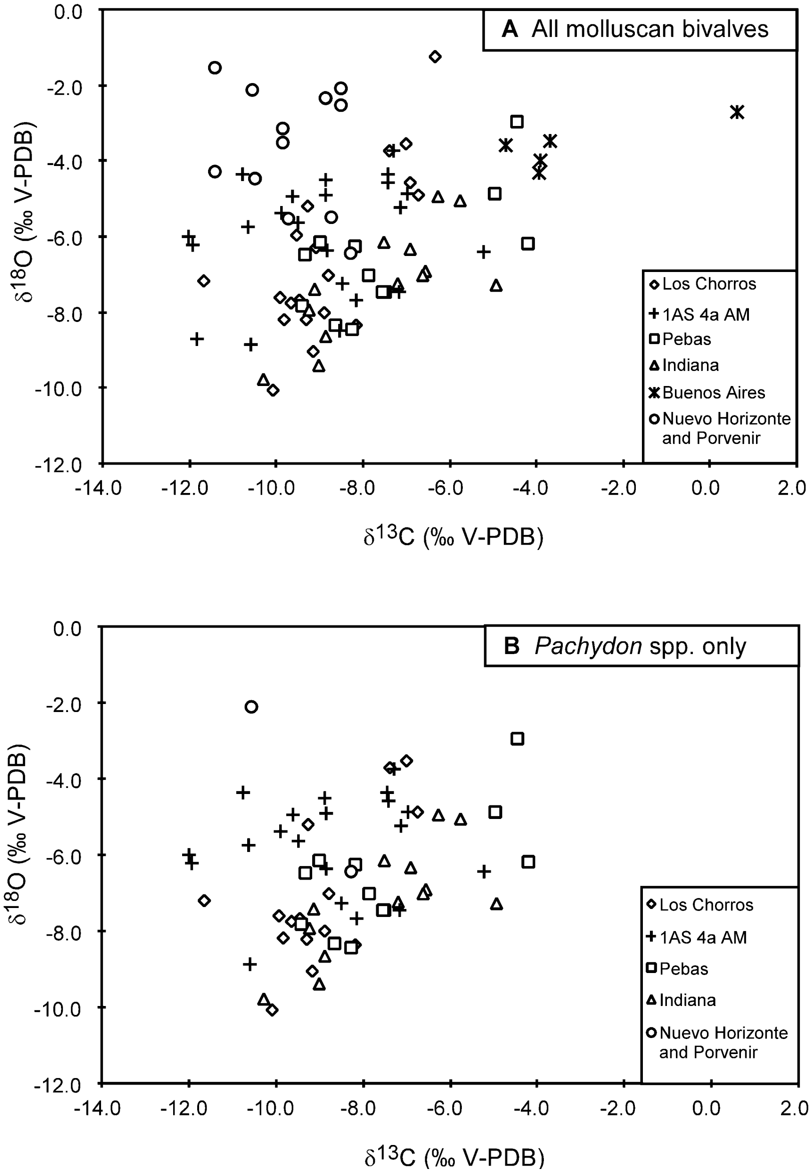

Figure 6. $\delta^{18}O$ and $\delta^{13}C$ cross plots of (A) all chemically well-preserved Pebas Formation mollusk shell samples analyzed, and (B) chemically well-preserved mollusk shell samples of only the common genus *Pachydon*.

freshwater interpretation for these sections based on $^{87}Sr/^{86}Sr$ ratios alone. Particularly in core 1AS–4a-AM, the interval from 80 to 140 m with high $^{87}Sr/^{86}Sr$ ratios suggests the prolonged existence of a cratonic freshwater hinterland at that location.

To visualize the robustness of paleosalinity zonations over a wide range of Andean runoff compositions, we have repeated salinity calculations for even more extreme Andean $^{87}Sr/^{86}Sr$ values. In Figure 7B, we applied the $^{87}Sr/^{86}Sr$ ratio of 0.7059 from the Napo River (Table 2), which is the river with the lowest $^{87}Sr/^{86}Sr$ ratio reported from the Amazon Basin. The plot shows that even under the unlikely assumption that this $^{87}Sr/^{86}Sr$ ratio was representative for all Andean runoff, Pebas Formation mollusks yield maximum calculated salinities of ~1 psu. It appears therefore that over a large range of Andean freshwater compositions, these salinity calculations are very robust and indicate dominant freshwater conditions for the Pebas Formation.

Depositional Setting

Most of the analyzed Pebas Formation mollusks fall in a $^{87}Sr/^{86}Sr$ range between 0.7077 and 0.7085, which is in the range of modern rivers from the two nearest Andean freshwater subbasins: the Northern Andes subbasin and the Ucayali-Marañon subbasin (Fig. 3B). Apparently, the rivers of the Madeira subbasin as well as the cratonic rivers were hydrologically separated from our study area for most of middle to late Miocene time (with a notable exception for core 1AS–4a-AM).

The middle Miocene *Crassoretitriletes* pollen zone is represented in the Pebas outcrop group and in core 1AS–4a-AM. Between these two records, there appears to be little $^{87}Sr/^{86}Sr$ overlap. High $^{87}Sr/^{86}Sr$ values in core 1AS–4a-AM suggest that it was part of a cratonic catchment during most of the deposition of the *Crassoretitriletes* zone, whereas low molluscan $^{87}Sr/^{86}Sr$ ratios of the Pebas outcrop group clearly belong to an Andean catchment. Although the data are far from comprehensive, this comparison seems to suggest that our study area was hydrologically subdivided in the late middle Miocene. Possible tectonic activity of a number of so-called structural arches (see Räsänen et al., 1990; Hoorn et al., 1995; Campbell, 2001) may have played a role in the subdivision of Western Amazonian catchments.

For the middle to late Miocene *Grimsdalea* pollen zone, molluscan $^{87}Sr/^{86}Sr$ values from different locations (core 1AS–4a-AM, Porvenir, Los Chorros) fall in a narrow range of 0.7080–0.7085. Although exact correlations between the different outcrops and the core cannot be made, these comparable $^{87}Sr/^{86}Sr$ ratios may point toward an undivided Western Amazonian catchment at these times. Because sedimentological evidence suggests deposition in a shallow-water coastal setting, the late Miocene Pebas environment may have been a hydrologically well-mixed, shallow-water lacustrine system, predominantly fed by Andean catchments. Occasional influence of marine incursions into this system is documented in the Buenos Aires section.

Our Sr isotope results are at odds with a number of previous studies that suggest significant marine influence in the Pebas system (Räsänen et al., 1995; Webb, 1995; Monsch, 1998). In particular, discrepancies exist with recent work on the ichnofauna of the Pebas Formation that suggested common mesohaline to polyhaline conditions (Räsänen et al., 1998; Gingras et al., 2002).

A strikingly similar case was described for the Lower Cretaceous Manville Group in North America (Holmden et al., 1997). Holmden and coworkers observed isotopic signatures in freshwater mollusk shells from strata with paleontological brackish-water indicators (including palynomorphs and ichnofauna). To explain these seemingly contradictory obser-

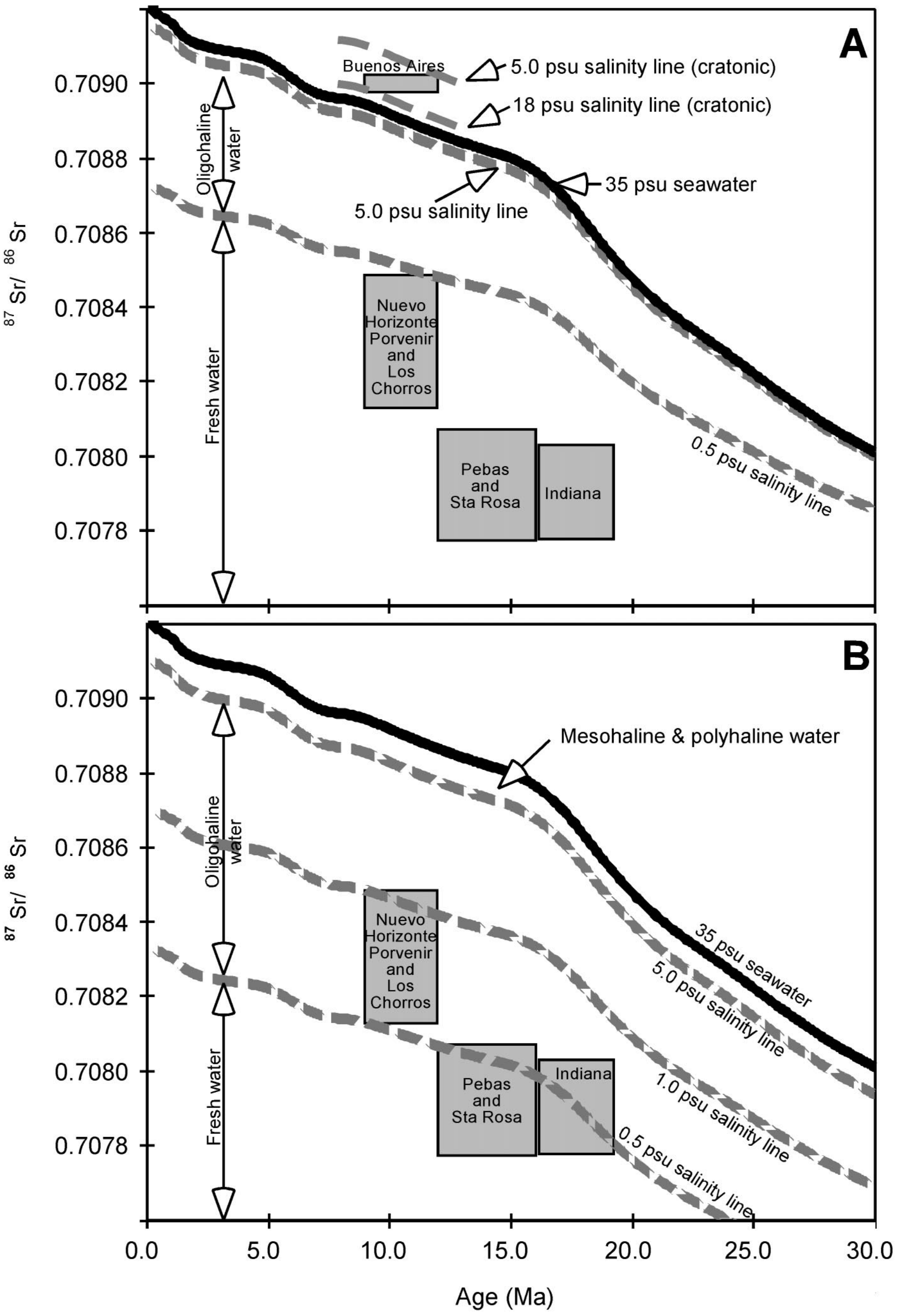

Figure 7. Molluscan $^{87}Sr/^{86}Sr$ ranges of Pebas Formation outcrops plotted over their full palynostratigraphic range. Superimposed are the paleosalinity fields for this part of the Neogene calculated with equation 1, on the basis of a marine $^{87}Sr/^{86}Sr$ reference curve (black line; data from Howarth and McArthur [1997]) and two different Andean freshwater end-member compositions. (A) Andean freshwater end member at a $^{87}Sr/^{86}Sr$ ratio of 0.7074 and a Sr concentration of 0.0416 μmol/L (Tables 2 and 3). Two short broken lines around the data from the Buenos Aires outcrop group indicate salinity fields in a seawater + cratonic freshwater mixture, which only applies to this specific outcrop (see text). (B) Similar to Figure 7A, but calculated with Andean freshwater composition equal to that of the modern Napo River. ($^{87}Sr/^{86}Sr$ = 0.7059 at 0.0416 μmol/L Sr; Palmer and Edmond, 1992).

vations, they proposed a system "with a restricted marine connection, similar in conception to modern Lake Maracaibo." Lake Maracaibo (in Venezuela) is a large embayment with a narrow connection to the Caribbean Sea. Freshwater supply to the lake is sufficient to sustain comparatively low salinities; southern Lake Maracaibo is essentially a freshwater environment. At the same time, the restricted connection to the Caribbean Sea allows brackish-marine organisms to enter Lake Maracaibo, possibly transported with tidal currents near the inlet of the lake. Given time, this could lead to the development of endemic fresh- to brackish-water faunas, which are not readily comparable to faunas from less restricted, brackish-water environments (Wesselingh et al., 2002).

For the Pebas Formation, an interpretation of a long-lived Maracaibo-type depositional environment would be in good agreement with the following observations: (1) extensive endemism in aquatic taxa (Wesselingh et al., 2002), (2) mixed freshwater and brackish-water fauna in isotopically fresh waters, (3) microtidal sedimentary structures (Räsänen et al., 1995, 1998), and (4) rare brackish-water incursion levels in the Buenos Aires outcrop identified with molluscan $^{87}Sr/^{86}Sr$ ratios (this study).

A possible seawater source to Western Amazonia is the Los Llanos Basin, north of our study area (Fig. 3A), which is thought to have been the site of several marine phases through the Oligocene and Miocene (Hoorn et al., 1995; Lundberg et al., 1998; Villamil, 1999). Brackish-water biota are predominantly (but not exclusively) found in records from the *Grimsdalea* pollen zone (Hoorn, 1993, 1994b; Monsch, 1998; Vonhof et al., 1998; Wesselingh et al., 2002), suggesting that a restricted connection to the Los Llanos Basin existed at that time.

The Vaupes structural arch (Fig. 3A) forms the main barrier between the Los Llanos Basin and Western Amazonia. The Buenos Aires mesohaline-incursion mollusk shells carry a cratonic freshwater signature, suggesting that marine water from the Los Llanos Basin entered Western Amazonia along the Eastern margin of the Vaupes structural arch, mixed with fresh water from the Guyana craton (cf. Vonhof et al., 1998). Such a restricted marine connection to Western Amazonia may have been controlled by eustatic sea-level change or by tectonic activity of the Vaupes structural arch and the Los Llanos portal. Currently, our stratigraphic control on the incursion level at Buenos Aires is not good enough to compare it to eustatic sea-level curves in any detail.

CONCLUSIONS

The sedimentology of the Pebas Formation sequences studied points toward relatively shallow-water lacustrine and swamp environments. The bulk of $^{87}Sr/^{86}Sr$ ratios from the Pebas Formation mollusks occupies a relatively narrow range (~0.7077–0.7086), indicating that fresh water input was dominantly from Andean catchments. Occasional communication with other catchments resulted in episodic input of higher (cratonic) fresh water $^{87}Sr/^{86}Sr$ ratios (as seen in CPRM core 1AS–4a-AM) or in brackish-water incursion events (as seen in the Buenos Aires outcrop).

Molluscan $^{87}Sr/^{86}Sr$ ratios for the Buenos Aires outcrop yielded mesohaline conditions in our model. Increased salinities were not only recorded in molluscan $^{87}Sr/^{86}Sr$ values, but also in increased Sr concentrations, in relatively high $\delta^{13}C$ values, and in the presence of taxa with meso- or polyhaline modern relatives.

All other outcrops yielded strictly freshwater-mollusk $^{87}Sr/^{86}Sr$ ratios. Even though we applied two freshwater end members (Andean and cratonic runoff), our calculations represent maximum salinities.

Venezuelan Lake Maracaibo may be a suitable modern analogue for the Pebas Formation depositional environment, because that lake's setting allows for the occurrence of tides and brackish-marine organisms in a dominantly freshwater environment (cf. Holmden et al., 1997). The Vaupes structural arch is postulated to have formed the restricted connection to the brackish-marine Miocene Los Llanos Basin. Eustatic sea-level change and tectonic activity involving the Vaupes structural arch and Los Llanos Basin may have controlled this restricted marine connection between the Caribbean Sea and Western Amazonia.

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