sphere, we have calculated the atmospheric residence time of MeONO₂ and EtONO₂. Use of the mean sea-to-air fluxes for 0° to 40°S (Table 1) and measured atmospheric concentrations results in a lifetime of between 4.5 and 25 days for MeONO₂ and between 6 and 10 days for EtONO₂. (22) Literature estimates of the atmospheric lifetime of MeONO₂, based on known atmospheric destruction processes, are poorly constrained, ranging from 6 to 29 days (23, 24). For EtONO₂, the atmospheric lifetime with respect to photodissociation at the equator and at 40°S has been estimated to be 7 and 12 days, respectively, for October (25). The reasonable agreement between the two methods implies that, for this region at least, the oceanic flux of these light alkyl nitrates is a significant source component of the light alkyl nitrate budget, thereby satisfying the requirements of the reported atmospheric measurements for a marine source.

References and Notes
13. Surface water samples, taken from the ship’s pumped nontoxic supplies, were collected at 2- to 4-hour intervals in 100-ml glass light syringes. Seawater was pumped from a depth of ~7 m during AMT 9 and ~11 m during AMT XVIII/1. During AMT 9, daily depth profiles were also carried out, in which seawater samples, collected at 0.6 m intervals, were taken from Niskin bottles mounted on a Seabird conductivity temperature depth (CTD) rosette. Air samples, collected in conjunction with surface water samples, were pumped into 3-liter electropolished stainless steel cylinders from the bow of the ship (~15 m above sea level) when the wind direction was within ±90° of the bow, in order to avoid contamination from the ship’s stack.
14. Water samples (40 ml) were typically analyzed within 4 hours of collection. During depth profiling, samples were unavoidably stored for up to 10 hours and were kept in the dark under running seawater. Air samples (600 ml) were analyzed within 2 hours of collection. Both sample types were injected into the same volatile extraction and preconcentration system. The volatile compounds were concentrated on an empty stainless steel sampling loop (30 cm length, 0.03” internal diameter) positioned above the temperature-controlled headspace of a liquid nitrogen–filled dewar. The analyte was extracted into the GC column (DB 624, 60 m length, 0.53 mm outer diameter, and 3 μm phase thickness) by heating the trap to ~100°C using boiling water. The column was temperature-programmed from 35° to 290°C at a rate of 1°C/min. Detector linearity, and storage artefacts were performed on board. Peak precision for MeONO₂ and EtONO₂ was ~11%, based on the analysis of triplicate seawater samples.

REPORTS

Subduction and Recycling of Nitrogen Along the Central American Margin

Tobias P. Fischer,* David R. Hilton, Mindy M. Zimmer, Alison M. Shaw, Zachary D. Sharp, James A. Walker

We report N and He isotopic and relative abundance characteristics of volatiles emitted from two segments of the Central American volcanic arc. In Guatemala, δ¹⁵N values are positive (i.e., greater than air) and N₂/He ratios are high (up to 25,000). In contrast, Costa Rican N₂/He ratios are low (maximum 1483) and δ¹⁵N values are negative (minimum –3.0 per mil). The results identify shallow hemipelagic sediments, subducted into the Guatemalan mantle, as the transport medium for the heavy N. Mass balance arguments indicate that the subducted N is efficiently cycled to the atmosphere by arc volcanism. Therefore, the subduction zone acts as a “barrier” to input of sedimentary N to the deeper mantle.

The present-day isotopic composition of N (δ¹⁵N) is different in the various terrestrial reservoirs. For example, the mantle supplying mid-ocean ridge basalts (MORB) is depleted in δ¹⁵N (~–5 permil (‰)) compared with Earth’s atmosphere (~2–7‰). The isotopic difference between mantle and atmospheric N is probably established early in Earth’s history, reflecting the integrated effects of partial outgassing of primordial N, possible late addition of asteroidal and/or cometary N, and/or hydrodynamic escape of a primary atmosphere (~8–11). Subsequent modifications to the N isotope balance between the mantle and atmosphere may have occurred through subduction of biogenic and terrigenous sediments into the mantle (12). Sedimentary material also has a N isotopic composition (δ¹⁵N = +6 to +7‰) distinct from the atmosphere and upper mantle (13, 14) resulting from a kinetic isotope effect that has enriched (residual) nitrogen in δ¹⁵N (~15–17). This large isotopic contrast between mantle and crustal/atmospheric reservoirs gives N potential as a tracer of volatile recycling between the surface and Earth’s interior. Here we focus on volatile exchange associated with the sub-
duction process and specifically on the N isotope systematics of the volcanic arc of Central America.

Central America is the site of active subduction of the Cocos Plate beneath the Caribbean Plate. Resulting volcanism occurs along a linear front extending some 1100 km from the Guatemala-Mexico border to central Costa Rica. Volcanoes tend to occur as large composite volcanic centers, with an average spacing of ~25 km—which is less than the spacing at other subduction zones (18, 19). There is no geophysical evidence for sediment accretion along the Central American arc, implying that the bulk of the sediments on the downgoing Cocos Plate are subducted into the mantle (20–23). Deep sea drilling sites off Guatemala/El Salvador (site 495) and Costa Rica (site 1039) have revealed the nature of these deep oceanic sediments (24, 25).

### Table 1. Nitrogen and helium isotope and relative abundance characteristics of Central American volcanic gases. Guatemala samples were taken in May 2001, Costa Rica samples in January, March, and July 2001. Type code: GF, gas from fumarole; GS, gas from (hot) spring; GW, gas from geothermal well; GM, gas from mudpot. Nitrogen source codes denote fraction of nitrogen derived from air (A), mantle (M), and sediment (S); see (28) for calculation of these fractions. nd, Not determined; stm, steam.

<table>
<thead>
<tr>
<th>Volcano/location</th>
<th>Lat. (N)</th>
<th>Long. (W)</th>
<th>Temp. (°C)</th>
<th>Type</th>
<th>δ15N (%o)</th>
<th>3He/He (RHe/RHe)*</th>
<th>N2 (mmol/mol)</th>
<th>N2/He</th>
<th>Nitrogen source</th>
<th>%S†</th>
<th>δ15N‡ (%o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guatemala</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zunil</td>
<td>14°</td>
<td>91°</td>
<td>93.0</td>
<td>GF</td>
<td>1.9 ± 0.5</td>
<td>4.69 ± 0.05</td>
<td>0.006</td>
<td>5139 ± 524</td>
<td>A</td>
<td>0.69</td>
<td>0.29</td>
</tr>
<tr>
<td>Zunil</td>
<td>46.693°</td>
<td>30.54’</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>92.3</td>
</tr>
<tr>
<td>San Marcos</td>
<td>nd</td>
<td>nd</td>
<td>94.7</td>
<td>GS</td>
<td>1.3 ± 0.4</td>
<td>2.23 ± 0.03</td>
<td>0.034</td>
<td>6691 ± 682</td>
<td>A</td>
<td>0.78</td>
<td>0.20</td>
</tr>
<tr>
<td>La Cimarron</td>
<td>14°</td>
<td>28.590°</td>
<td>87.7</td>
<td>GF</td>
<td>5.7 ± 0.2</td>
<td>6.95 ± 0.06</td>
<td>0.090</td>
<td>2227 ± 227</td>
<td>A</td>
<td>0.09</td>
<td>0.85</td>
</tr>
<tr>
<td>La Cimarron</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>94.0</td>
</tr>
<tr>
<td>Volcan Fuego</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.28</td>
</tr>
<tr>
<td>Summit</td>
<td>14°</td>
<td>90°</td>
<td>52.816°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amatitlan-Pacaya</td>
<td>14°</td>
<td>28.395°</td>
<td>36.140°</td>
<td>GS</td>
<td>-0.5 ± 0.4</td>
<td>6.72 ± 0.07</td>
<td>1.595</td>
<td>9748 ± 994</td>
<td>A</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lake Shore</td>
<td>14°</td>
<td>27.074°</td>
<td>38.572°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot water dyke</td>
<td>14°</td>
<td>90°</td>
<td>76.4</td>
<td>GS</td>
<td>2.1 ± 0.2</td>
<td>6.22 ± 0.06</td>
<td>2.324</td>
<td>4385 ± 447</td>
<td>A</td>
<td>0.65</td>
<td>0.32</td>
</tr>
<tr>
<td>Laguna de caldera</td>
<td>14°</td>
<td>90°</td>
<td>35.807°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>91.8</td>
</tr>
<tr>
<td>Laguna de caldera</td>
<td>14°</td>
<td>24.695°</td>
<td>35.807°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.01</td>
</tr>
<tr>
<td>Laguna de caldera</td>
<td>14°</td>
<td>24.695°</td>
<td>35.807°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tecomucurro</td>
<td>14°</td>
<td>11.577°</td>
<td>25.394°</td>
<td>GS</td>
<td>5.9 ± 0.3</td>
<td>6.38 ± 0.06</td>
<td>0.468</td>
<td>7734 ± 789</td>
<td>A</td>
<td>0.14</td>
<td>0.85</td>
</tr>
<tr>
<td>Laguna Ixchaco</td>
<td>14°</td>
<td>11.577°</td>
<td>25.394°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>99.3</td>
</tr>
<tr>
<td>Duplicates (LI)</td>
<td>14°</td>
<td>90°</td>
<td>77.8</td>
<td>GS</td>
<td>5.9 ± 0.3</td>
<td>6.38 ± 0.06</td>
<td>0.468</td>
<td>7734 ± 789</td>
<td>A</td>
<td>0.14</td>
<td>0.85</td>
</tr>
<tr>
<td>Sulfur mine</td>
<td>14°</td>
<td>90°</td>
<td>93.1</td>
<td>GF</td>
<td>-0.7 ± 0.5</td>
<td>5.39 ± 0.06</td>
<td>1.015</td>
<td>24,899 ± 2539</td>
<td>A</td>
<td>0.43</td>
<td>0.49</td>
</tr>
<tr>
<td>Sulfur mine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moyuta</td>
<td>14°</td>
<td>90°</td>
<td>85.9</td>
<td>GS</td>
<td>4.3 ± 0.4</td>
<td>7.39 ± 0.06</td>
<td>0.519</td>
<td>6042 ± 616</td>
<td>A</td>
<td>0.36</td>
<td>0.63</td>
</tr>
<tr>
<td>Las Guineas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>97.6</td>
</tr>
<tr>
<td>Mirram “El Volcan”</td>
<td>14°</td>
<td>90°</td>
<td>80.7</td>
<td>GM</td>
<td>1.8 ± 0.3</td>
<td>7.36 ± 0.09</td>
<td>0.72</td>
<td>6629 ± 676</td>
<td>A</td>
<td>0.26</td>
<td>0.02</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>10°</td>
<td>11.883°</td>
<td>84°</td>
<td>GF</td>
<td>-1.9 ± 0.3</td>
<td>7.10 ± 0.10</td>
<td>0.020</td>
<td>101 ± 10</td>
<td>A</td>
<td>0.00</td>
<td>0.26</td>
</tr>
<tr>
<td>Poas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>75.7</td>
</tr>
<tr>
<td>Crater – 1/01</td>
<td>10°</td>
<td>11.883°</td>
<td>84°</td>
<td>GF</td>
<td>-2.7 ± 0.4</td>
<td>7.22 ± 0.07</td>
<td>0.023</td>
<td>268 ± 27</td>
<td>A</td>
<td>0.43</td>
<td>0.01</td>
</tr>
<tr>
<td>Crater – 3/01</td>
<td>10°</td>
<td>11.883°</td>
<td>84°</td>
<td>GF</td>
<td>-2.4 ± 0.5</td>
<td>7.14 ± 0.07</td>
<td>0.037</td>
<td>373 ± 38</td>
<td>A</td>
<td>0.52</td>
<td>0.01</td>
</tr>
<tr>
<td>Crater – 7/01</td>
<td>10°</td>
<td>11.883°</td>
<td>84°</td>
<td>GF</td>
<td>-3.0 ± 0.6</td>
<td>7.15 ± 0.07</td>
<td>0.021</td>
<td>156 ± 16</td>
<td>A</td>
<td>0.01</td>
<td>0.16</td>
</tr>
<tr>
<td>Turrialba</td>
<td>10°</td>
<td>11.883°</td>
<td>84°</td>
<td>GF</td>
<td>-2.7 ± 0.4</td>
<td>7.22 ± 0.07</td>
<td>0.023</td>
<td>268 ± 27</td>
<td>A</td>
<td>0.43</td>
<td>0.65</td>
</tr>
<tr>
<td>Summit</td>
<td>10°</td>
<td>11.883°</td>
<td>84°</td>
<td>GF</td>
<td>-2.4 ± 0.5</td>
<td>7.14 ± 0.07</td>
<td>0.037</td>
<td>373 ± 38</td>
<td>A</td>
<td>0.52</td>
<td>0.01</td>
</tr>
<tr>
<td>Summit</td>
<td>10°</td>
<td>11.883°</td>
<td>84°</td>
<td>GF</td>
<td>-3.0 ± 0.6</td>
<td>7.15 ± 0.07</td>
<td>0.021</td>
<td>156 ± 16</td>
<td>A</td>
<td>0.01</td>
<td>0.16</td>
</tr>
<tr>
<td>Turrialba</td>
<td>10°</td>
<td>11.883°</td>
<td>84°</td>
<td>GF</td>
<td>-2.7 ± 0.4</td>
<td>7.22 ± 0.07</td>
<td>0.023</td>
<td>268 ± 27</td>
<td>A</td>
<td>0.43</td>
<td>0.65</td>
</tr>
<tr>
<td>Turrialba</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irazu</td>
<td>9°</td>
<td>59.723°</td>
<td>83°</td>
<td>GF</td>
<td>1.0 ± 0.3</td>
<td>7.24 ± 0.06</td>
<td>0.537</td>
<td>1483 ± 151</td>
<td>A</td>
<td>0.59</td>
<td>0.31</td>
</tr>
<tr>
<td>Irazu</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Corrected for the effects of air-derived helium [55]. Error quoted at the 1σ level. †Percentage of sediment-derived nitrogen in binary sediment-mantle mixture. ‡Measured nitrogen isotope ratios are corrected for air contamination using δ15N = f δ15Nair + (1 - f)δ15Nmantle, where δ15Nair = -5‰, δ15Nmantle = +7‰, and f is the fraction of mantle-derived nitrogen [calculated from permutative column: f = 1 - (δ15Nair/100)]. §Estimated value derived by projecting data point onto M-S mixing curve [N2/He = 200 for Poas crater 1/01; N2/He = 312 for Poas crater 7/01; N2/He = 750 for Turrialba]. ††Average of three other ratios at same locality.
little regional variation in the sedimentary sequences on the oceanic plate: The sediment column consists of \( \sim 175 \) m of hemipelagic, diatom-rich mud overlaying \( \sim 250 \) m of pelagic carbonates (20, 21, 24, 25). Both units are geochemically distinct and contribute to volcanic sources along much of the strike of the arc (24, 26). In Costa Rica, however, the low \(^{10}Be\) contents of arc magmas suggest that the hemipelagic portion of the sedimentary column is underplated to the overriding Caribbean Plate, leaving only the pelagic carbonates to contribute to the slab flux (27). This variation in the amount and type of sediment involved in petrogenesis makes Central America an ideal locality to investigate details of the transfer of N into the mantle and the associated effects on \( N_2/He \) and \(^{15}N \) ratios.

We measured N concentrations, \( N_2/He \) ratios, and N and He isotopic compositions of gas discharges of three volcanic centers in Costa Rica and six volcanic regions in Guatemala (Table 1) (28). The majority of samples have \(^{3}He/^{4}He\) ratios in the range 5 to 8 \( R_\lambda \), (where \( R_\lambda \) is the \(^{3}He/^{4}He\) value of air = \( 1.4 \times 10^{-8} \)), indicating that both segments of the arc sample He primarily from the mantle wedge (29, 30). In contrast, the N isotope systematics and \( N_2/He \) ratios vary between Guatemala and Costa Rica. The Guatemalan volatiles have \(^{15}N \) values that are mostly greater than AIR (1) (i.e., positive, from \(-0.5 \) to \( 6.3\% \)); they also have associated \( N_2/He \) ratios falling between 1400 and 25,000, consistent with the range found previously in arc-related volcanoes (31). Volatiles from Costa Rica, however, have lower \( N_2/He \) ratios (101 to 1483) and mostly negative \(^{15}N \) ratios (\(-3.0 \) to \( +1.7\% \)).

Addition of (sediment-derived) N to mantle sources is expected to result in higher \( N_2/He \) ratios and more positive \(^{15}N \) values; these trends are observed for the Guatemala samples in general and for Fuego Volcano and Laguna Ixpaco in particular (Fig. 1). Assuming that N and He are not fractionated by magmatic or hydrothermal processes (28), we estimated the proportion of N derived from sediment and the mantle wedge (Table 1) (28). We find that the Guatemala samples are dominated by sediment-derived N. In contrast, volcanic gases in Costa Rica have a much lower proportion of N derived from sedimentary material. At both Turrialba and Poas volcanoes, there is no discernible contribution from sedimentary N, and the N (after correction for air) is solely of mantle origin.

We also considered the possibility that the arc crust through which magmas are erupted may contribute to the N inventory. The presence of radiogenic helium (\(^{3}He/^{4}He \sim 0.05 R_\lambda \)) in arc-related environments is a particularly sensitive indicator of crustal additions to the volatile budget (32, 33). If we define \( 5.4 R_\lambda \) as a lower limit for mantle wedge He (34), then all Guatemala samples—with the exception of Zunil (4.7 \( R_\lambda \)) and San Marcos (2.2 \( R_\lambda \))—record binary mantle wedge–subducted sediment mixing with a maximum contribution of \(-6\% \) sediment (Fig. 2). The two exceptions record the effects of crustal contamination leading to lower \(^{3}He/^{4}He \) ratios than anticipated for the sub-arc mantle. The sediment contribution for Costa Rica samples reaches a maximum of \( \sim 0.7\% \). We conclude, therefore, that the He-N isotope systematics are compatible with binary mixing between the mantle wedge and subducted sediment, with Costa Rica recording little or no contribution from the sedimentary end member and Guatemala magmas recording up to \(-6\% \).

The N-He isotope and relative abundance systematics identify the uppermost hemipelagic section of material being subducted as the carrier of sedimentary N to the source region of the Central American arc magmas. The lack of this component in the source region of the Central American magmas—consistent with the low \(^{10}Be \) and notions of underplating in the region (27)—results in samples from Poas and Turrialba being devoid of a sediment-derived N component. In addition, because the Costa Rica samples lack any sediment-derived N, the pelagic carbonates (which are subducted along the entire strike of the Central American margin) cannot contribute N to the source of arc magmas beneath Costa Rica or Guatemala. Either pelagic carbonates contain no sedimentary N (35) or they are sufficiently stable to retain any N throughout the subduction cycle. Given evidence that carbonate sediments do contribute to the source of arc magmas throughout Central America [based on Ba/Th ratios, for example (24, 26)] and the fact that CO\(_2/^{3}He\) ratios are high \([\geq 10^{10}\] (36–38)], the carbonate sediments probably do not contain N.

With the identification of hemipelagic muds as the principal carrier of sedimentary-derived N into the mantle, we now determine whether a mass balance exists between the input of this sedimentary-derived N via the trench adjacent to Central America and its output via volcanism along the arc. A recent estimate (39) of the total input of N into the Central American subduction zone is \( 5.5 \times 10^{8} \) mol/year, based on the flux of sedimentary material and an assumed N concentration in oceanic sediments of 0.01 wt %. This approach, however, assumes a homogeneous distribution of N throughout the entire sedimentary pile (\(-425 \) m). If sediment-derived N is present in the uppermost hemipelagic portion only \( \sim 175 \) m (20, 21, 24, 25), then the above flux needs to be revised by a factor of 175/425 to give an input estimate for the entire Central American margin of \( 2.3 \times 10^{8} \) mol N/year.

The total output of N along the Central...
American margin has been estimated at 1.7 \times 10^7 mol/year by combining an estimate of the total SO$_2$ flux (2.1 \times 10^7 mol/year) with the median SO$_2$/N$_2$ ratio (12.6) derived from almost 100 analyses of volcanic gas chemistries in the region (39). The above flux can be corrected for air-derived N on the basis of measured N/Ar ratios and the assumption that Ar is derived from air. The revised value for the non-air N flux from the Central American arc is 2.9 \times 10^8 mol/year (39). This output flux balances almost exactly the input flux of N into the trench and implies that N is efficiently released from the slab and transported through the mantle wedge to the atmosphere by arc volcanism. Thus, the Central American subduction zone acts as a “barrier” (40) for the transport of sedimentary N into the mantle beyond the region of magma formation below the arc; that is, the N transfer from the crust to deep mantle is short-circuited by release through arc volcanism.

If the Central American subduction zone acts to efficiently recycle sediments into the deeper mantle, other than shallow marine sediments:  

28. Materials and methods are available on Science Online.  
31. Other arc-related volcanoes analyzed for N systematics include Satsuma-Iwojima (42), Taupo Volcanic Zone (43), and Kudryashev (44). Javoy et al. (2) showed that Pao has negative 84N values. A review of arc-related volcanic gases is provided by Giggenbach (45).  
34. Hilton et al. (46) produced a “global” estimate of the isotopic composition of mantle wedge helium (5.4 R$_a$) based on a compilation of >1000 He/He ratios at arcs worldwide.  
35. Bebout (47) notes that the N concentration in oceanic pelagic sediments can vary from 70 to 600 ppm; however, pelagic limestone (100% calcite) may contain essentially no N.  
39. Hilton et al. (46) made N-input and N-output estimates for Central America and for arcs globally. In the case of Central America, the N-input estimate was based on a value of 7.7 \times 10^8 g sediment subducted over the entire length (1100 km) of the Central America trench (48).  
40. Staudacher and Allègre (49) first used the term “barrier” in the context of processing noble gases at subduction zones.  
41. Plank and Langmuir (48) calculate an average global subducting sediment (GLOSS) composition. The error on trace elements contents is 10 to 50%.  
53. A. M. Shaw et al., in preparation.  
54. Air has N$_2$/He = 1.489 \times 10^7 [50], N$_2$/He, of the mantle is taken as 150 using a compilation of global N-MORB values (51). N$_2$/He$_{M}$ = 10,000 is obtained by combining an estimate of 2 \times 10^7 g for the crustal N$_2$/Ar ratio (52) with a He/He$_{M}$ production ratio of 2 (50).  
55. See (52) for details of the correction procedure.  
56. Measured ratios are reported in (53).  
57. N$_2$/Ar = N$_2$/N$_2$, He$_{M}$/He$_{M}$. Adopting end member compositions from (54) gives a K of 70 (i.e., 10,500/150).  
58. Supported by NSF grants EAR-0017942 MARGINS and EAR-0003668 (T.P.F., EAR-0003628 (D.R.H.), and EAR-0003664 (J.A.W.), G. Alvarado and E. Molina provided logistical support during field work, and we thank C. Ramirez, B. Cameron, E. Mickelson, W. Suiter, and J. Hierhold for field assistance. V. Atudorei helped with N isotope analyses. We thank two anonymous reviewers for helpful comments.

Splay Fault Branching Along the Nankai Subduction Zone

Jin-Oh Park, Tetsuro Tsuru, Shuichi Kodaira, Phil R. Cummins, Yoshiyuki Kaneda

Seismic reflection profiles reveal steeply landward–dipping splay faults in the rupture area of the magnitude (M) 8.1 Tonankai earthquake in the Nankai subduction zone. These splay faults branch upward from the plate-boundary interface (that is, the subduction zone) at a depth of ~10 kilometers, ~50 to 55 kilometers landward of the trough axis, breaking through the upper crustal plate. Slip on the active splay fault may be an important mechanism that accommodates the elastic strain caused by relative plate motion.

Large thrust zones along subduction zone poses a seismic and tsunami threat to densely populated coastal cities. These earth-