Seismic Evidence for a Lower-Crustal Detachment Beneath San Francisco Bay, California

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Results from the San Francisco Bay area seismic imaging experiment (BASIX) reveal the presence of a prominent lower crustal reflector at a depth of ~15 kilometers beneath San Francisco and San Pablo bays. Velocity analyses indicate that this reflector marks the base of Franciscan assemblage rocks and the top of a mafic lower crust. Because this compositional contrast would imply a strong rheological contrast, this interface may correspond to a lower crustal detachment surface. If so, it may represent a subhorizontal segment of the North America and Pacific plate boundary proposed by earlier thermo-mechanical and geological models.

The relative motion between the North American and Pacific plates occurs over a wide zone in the San Francisco Bay Area (*1*), inconsistent with a single vertical plate boundary. Indeed, the region is cut by several faults including the San Andreas, Hayward, Rogers Creek, Calaveras, Concord, and Green Valley faults (Fig. 1). Seismicity maps show that all are active and capable of generating large-magnitude earthquakes (*2*, *3*). The occurrence of three pairs of large earthquakes (**M** > 6.5) on opposite sides of the Bay within 2 to 6 years of each other during the past 160 years (*2*) suggests that major strike-slip faults may be connected in the subsurface (*4*). A subhorizontal detachment surface in the middle or lower crust representing the plate boundary between the faults (*4–6*) has been proposed for this connection. The Bay Area seismic imaging experiment (BASIX) was initiated in September 1991 to obtain deep-crustal information that could be used to determine whether subhorizontal structures exist at depth.

The passage of the Mendocino triple junction through the San Francisco Bay region about 10 million years ago (Ma) formed a slab-free window, thermally weakened the lithosphere, and possibly formed a subhorizontal structure that mechanically links the San Andreas fault to the various fault strands across San Francisco Bay to the east [Hayward, Calaveras, Rodgers Creek, and other faults; (*4–6*)]. In these models, the subhorizontal structure occurs below seismogenic depths and primarily serves to connect the major fault strands to a deeper, vertical plate boundary between the Pacific and North American plates (*4*). Superimposed on the dominantly dextral strike-slip motion along the Pacific–North American plate boundary is a smaller (up to 10% of the horizontal strike-slip rate of 38 mm/year) component of fault-normal convergence (*1*, *7–9*) responsible for folding and thrusting in the Coast Ranges.

During BASIX, reflection and refraction data were acquired in the Suisun, San Pablo, and San Francisco bays, and on the continental shelf near the Golden Gate (Fig. 1). The U.S. Geological Survey (USGS) research vessel, *S. P. Lee*, towed the seismic source, consisting of a 12-element, 95.6-liter (5828 in.^{3}) airgun array. Multichannel seismic (MCS) reflection profiles (average of 40-fold) were recorded to 16-s two-way travel time using buoyed hydrophones deployed in the bays (*10*). In addition, wide-angle refraction data were recorded on 70 onshore and offshore stations as well as on the permanent earthquake seismic network in Northern California [Fig. 1 (*11*)]. These wide-angle seismic stations, stretching 260 km from the base of the continental rise to the foothills of the Sierra Nevada, produced shot-receiver offsets that ranged between 1 and 160 km (*11*).

Velocity analysis of the BASIX wide-angle data indicates that east of the San Andreas fault a (~200-m-thick) veneer of low-velocity (2 km/s) sediments are underlain by a 15-km-thick upper crustal layer with velocities of 5.5 to 6.2 km/s. Because Franciscan assemblage rocks are exposed throughout the Bay Area to the east of the San Andreas fault and are known to have a seismic velocity of 5.5 to 6.0 km/s (*12*), and because there are no observed seismic discontinuities (reflectors or refractors) at depths shallower than 15 km, we interpreted the Franciscan rocks to extend down to this depth.

The base of the Franciscan rocks is marked by a high-amplitude reflection at a two-way travel time of 6 s (~15 km, Fig. 2). This prominent event is observed on both the vertical-incidence and wide-angle BASIX profiles and can be mapped throughout the region. The limits of the reflector shown in Fig. 3 are defined by observed reflecting points and thus represent the minimum geographic extent of the reflector rather than its full extent. Wide-angle data permit us to map the reflector to greater lateral extent in the bays than do the MCS data; the limits of the reflector in the southern half of San Francisco Bay are

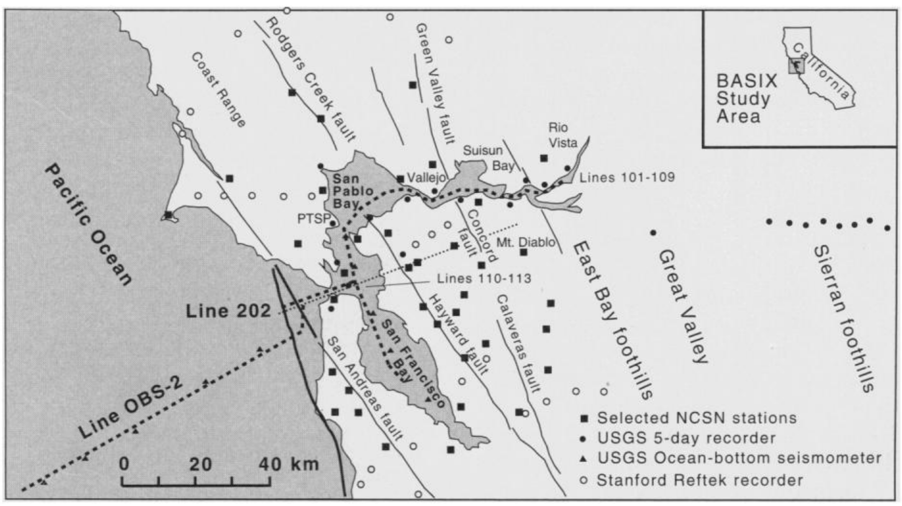

Fig. 1. Map of California (inset) showing the location of the BASIX study area in the San Francisco Bay Area. Index map shows the locations of major strike-slip faults, seismic reflection lines (dashed lines), and wide-angle recorders used to record lines (various symbols defined on figure). NCSN = Northern California Seismic Network. Thin dotted line gives location of cross sections shown in Fig. 4.

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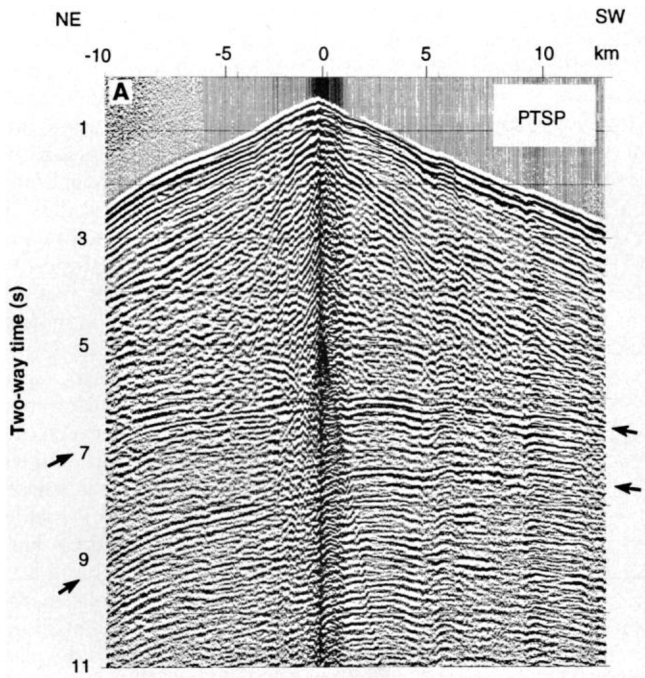

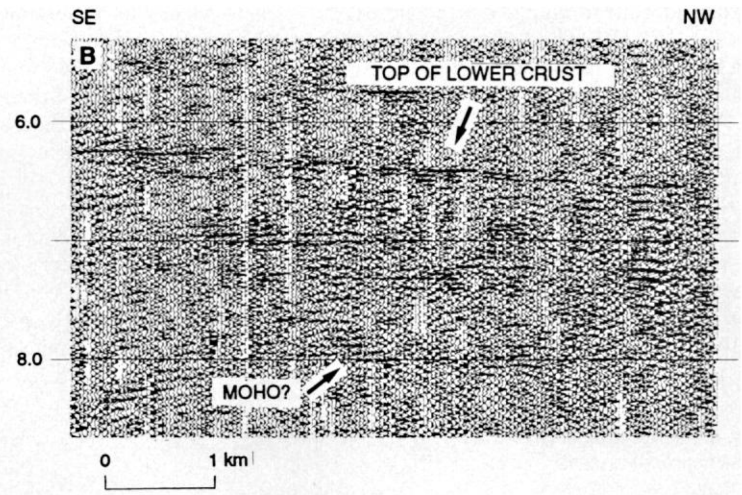

Fig. 2. (**A**) Seismic common-receiver gather illustrating prominent seismic reflectors at a two-way travel time of 6 and 8 s at zero offset (depths of approximately 15 and 22 km). Arrows show reflections that define a lower crustal layer that thins to the southwest. Seismic data were recorded at Point San Pedro (PTSP on Fig. 1), and have been deconvolved and plotted with a time-varying gain. (**B**) Portion of a multichannel seismic reflection gather from San Francisco Bay showing internal reflectivity associated with lower crustal layer (location shown in Fig. 3).

based entirely on wide-angle data. Although a small patch of reflector is identified on wide-angle data to the west of the San Andreas fault, the available information do not reveal whether the reflector is the same as that found on the other side of the fault or whether it is continuous across the fault. The 6-s reflector readily observed in the MCS data beneath the San Pablo and San Francisco bays is absent between Suisun Bay and Rio Vista, east of the Hayward fault (Figs. 1 and 3). The absence of this reflector on the MCS and on wide-angle data east of Suisun Bay may be real, because in this region there are excellent images of the upper crust to at least a two-way travel time of 3 s. It is also possible, however, that the seismic source was not sufficiently energetic to penetrate to the middle crust in this region.

On vertical-incidence recordings, the 6-s reflector is a high-amplitude event that marks the top of a zone of reflections in the lower crust (Fig. 2). Beneath the Golden Gate Bridge, these internal reflections pinch out up-dip against the 6-s reflector at the top of the packet. All lower crustal reflections are laterally discontinuous on a scale of hundreds of meters.

The velocity and thickness of the lower crustal layer are constrained by forward and inverse modeling (*13*) of wide-angle (>50 km offset) recordings of the 6-s reflector and the reflection from the crust-mantle boundary (Moho). These results (Fig. 4A) indicate that a layer with a thickness of 7 to 11 km and a velocity of 6.5 ± 0.2 km/s dips ~4° eastward beneath the continental slope and shelf. The top of the layer is ~13 km beneath the surface trace of the San Andreas fault.

We interpret that the lower crustal layer identified beneath the continental shelf and slope represents a slab of oceanic crust because it can be tracked to the seaward edge of the continental margin (Fig. 4A). In places this layer appears to be uncommonly (11 km) thick for oceanic crust (typically 5 to 7 km thick), and in these areas it may also be imbricated. These results are in general agreement with seismic studies conducted across the central California margin (*14*), in which a 5- to 6 km-thick slab of high-velocity material extending underneath the margin to the San Andreas fault was identified. Separate studies presented seismic refraction and wide-angle reflection evidence for a slab of oceanic crust beneath the continental slope and shelf offshore Santa Cruz, about 100 km south of the Golden Gate (*15, 16*). None of these studies, however, constrained the eastward limit of oceanic crust east of the San Andreas fault (*17*).

The results beneath San Francisco Bay indicate that the lower crust east of the San Andreas fault is 8 to 11 km thick. This thickness and the internal reflectivity that characterizes the lower crust suggest that it is not normal subducted oceanic crust. Assuming that the lower-crustal reflector is a detachment, which is consistent with the broad plate boundary inferred from geodetic models (*1*), we propose two alternative models for the lower crust beneath San Francisco Bay. The high seismic velocities (6.5 to 7.2 km/s; shown schematically as 6.9 km/s on Fig. 4A) indicate that the material most likely has a mafic composition. One set of possibilities is that the lower crust is a complex combination of

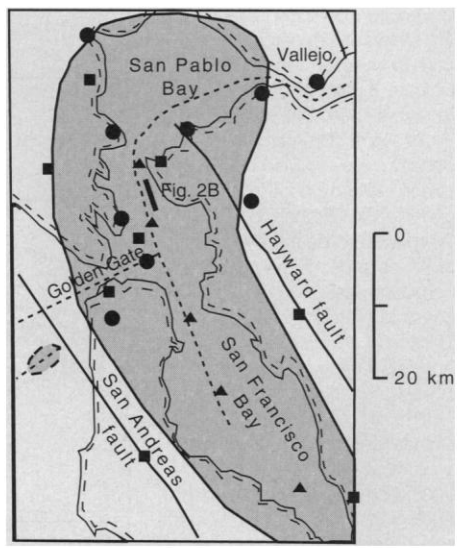

Fig. 3. Map of the San Francisco Bay Area showing in dark shading the minimum geographic extent of subhorizontal midcrustal reflections between a two-way travel time of 6 and 8 s (depth of approximately 15 to 22 km). Reflections are not observed east of Suisin Bay (Fig. 1). Reflections from airgun shots along the BASIX lines (dashed lines) were recorded by stations shown (symbols defined in Fig. 1) and some off the map. Note small isolated region seaward of the San Andreas fault determined from wide-angle reflections observed from line OBS2. Location of profile shown in Fig. 2B in northern San Francisco Bay is shown as heavy solid line.

(i) subducted oceanic crust (*15*), (ii) continental crystalline basement, or (iii) mantle-derived mafic material that has intruded and underplated the region during the passage of the Mendocino triple junction about 10 Ma (6, 18) (Fig. 4B). The lower crust likely was thickened by convergence during the past 5 million years.

An alternative model is that the high-velocity unit that underlies San Francisco Bay is the westward continuation of pre-Jurassic mafic basement of the Great Valley and Sierra Nevada (8, 19) (Fig. 4C). Interpretations of gravity and aeromagnetic data (20) suggest that this dense magnetic body continues westward beneath the Coast Ranges at least as far as the Hayward fault. The identification of a high-velocity mafic basement (6.8 to 7.2 km/s) beneath Mount Diablo and the East Bay foothills (21) and the Great Valley (22) further supports this interpretation.

We speculate that the 6-s reflector that separates Franciscan rocks from a mafic lower crust also represents a mechanical discontinuity, because of the dramatic contrast in rheology expected at the interface separating silicic (Franciscan) and mafic rocks (23). The prominent midcrustal reflector is continuous beneath the Hayward fault (Fig. 3), and the Moho is not offset across the San Andreas fault in wide-angle fan data. Thus, neither the San Andreas fault nor the Hayward fault cut the entire crust.

A continuous reflector across the major strike-slip faults implies that the relative motion between the North America and Pacific plates at depth occurs beneath the reflector. This observation, although not definitive given the relatively low dips on these surfaces and the resolution inherent in wide-angle data, is strongly suggestive that the midcrustal reflector acts as a detachment, displacing the strike-slip motion on these faults at midcrustal depths.

The implications of these results for earthquake hazards are twofold. If this feature serves as a subhorizontal link between the vertical strike-slip faults of the San Andreas system (4), it may help connect the stresses on these faults. Stress calculations modeling the effect of slip on the San Andreas fault indicate that incorporating a midcrustal horizontal detachment causes the faults in the East Bay to come closer to failure than allowing stress transmission only through the elastic crust (24). If in addition, this feature accommodates the smaller component of fault-normal convergence (8), some of the future seismicity will occur along any number of smaller and potentially blind thrust faults lying above the reflector. The entire system of Coast Range folds may be evolving in response to low-angle (blind) thrust faults that are rooted in a decollement near the base of the seismogenic crust (9). Because these faults are smaller and earthquakes on them have longer recurrence times, the seismic hazard they present has traditionally been downplayed in comparison to the larger strike-slip faults of the San Andreas fault system. The 1983 Coalinga and 1994 Northridge earthquakes elsewhere along the San Andreas fault system, however, have dramatically demonstrated the potential seismic threat from blind thrust faults (25).

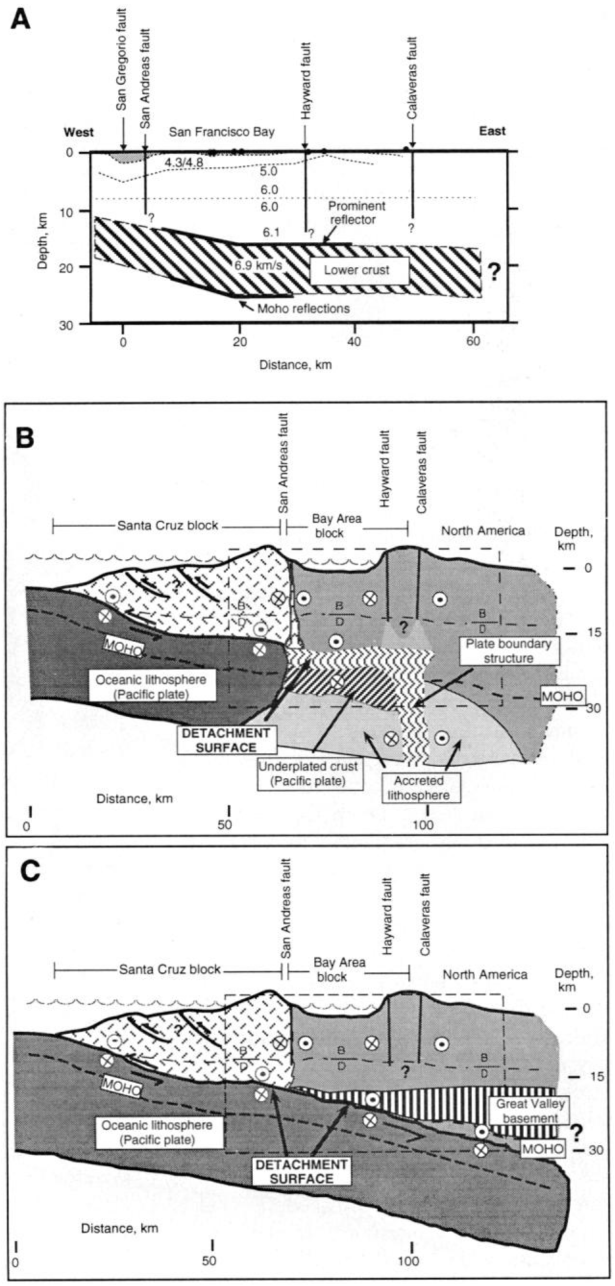

Fig. 4. Velocity model with two schematic interpretations of the subhorizontal reflector and crustal structure beneath San Francisco and San Pablo bays, based on BASIX lines at the latitude of the Golden Gate, and assuming that the lower-crustal reflector represents a detachment. (**A**) Velocity model showing location of prominent reflector at 15 km and the Moho. Thin, labeled dashed lines show isovelocity contours; velocities are shown in kilometers per second. Dots along tops of models indicate locations of wide-angle receivers used to record the BASIX lines. (**B**) Interpretation of velocity model in which the high-velocity lower-crustal rocks that underlie San Francisco Bay are interpreted to be the by-product of an episode of magmatic underplating associated with the passage of the Mendocino triple junction (*4, 18*). West of the San Andreas fault the lower crust is interpreted as oceanic crust of the Pacific plate. The Hayward and Calaveras faults extend nearly vertically through the entire lithosphere. The 15-km-deep lithological boundary also serves as a mechanical boundary, connecting the San Andreas fault with the major strike-slip faults of the East Bay (*4*). (**C**) Interpretation in which Franciscan rocks (velocities ≤6.1 km/s) beneath San Francisco Bay are underlain by a continuous, higher velocity (more mafic) layer (shaded), which we interpret as a single slab of oceanic crust, possibly of Pacific plate or captured Farallon plate (*15*). In addition, the pre-Jurassic Great Valley ophiolitic basement (vertically ruled) is shown extending beneath San Francisco Bay (*8, 19*), where it pinches out against the underlying oceanic crust. Circles with heads and tails of arrows show relative motion toward and away from the reader. For (B) and (C) dashed rectangle shows region covered by velocity model shown in (A). For (A) through (C), bold vertical lines at San Andreas, Hayward, and Calaveras faults show seismogenic portions of these fault zones, which we show as limited by the depth to the brittle-ductile transition (B/D).

REFERENCES AND NOTES

1. M. Lisowski, J. C. Savage, W. H. Prescott, *J. Geophys. Res.* **96**, 8369 (1991).
2. W. L. Ellsworth, *U.S. Geol. Surv. Prof. Pap. 1515* (1990), p. 153.
3. D. P. Hill, J. P. Eaton, L. M. Jones, *ibid.*, p. 115.
4. K. P. Furlong, *Tectonophysics* **223**, 149 (1993).
5. W. R. Dickinson and W. S. Snyder, *J. Geol.* **87**, 609 (1979); G. Zandt and K. P. Furlong, *Geology* **10**, 376 (1982).
6. K. P. Furlong, W. D. Hugo, G. Zandt, *J. Geophys. Res.* **94**, 3100 (1989).
7. B. M. Page and D. C. Engebretson, *Tectonics* **3**, 133 (1984); C. M. Wentworth, C. M. Blake Jr., D. L. Jones, A. W. Walter, M. D. Zoback, in *Franciscan Geology of Northern California*, M. C. Blake Jr., Ed. (Book 43, Society of Economic Paleontologists and Mineralogists, Pacific Section, Bakersfield, CA, 1984), pp. 163–173; M. D. Zoback *et al.*, *Science* **238**, 1105 (1987); J. R. Unruh and E. M. Moores, *Tectonics* **11**, 192 (1992).
8. D. L. Jones, R. Graymer, C. Wang, T. V. McEvilly, A. Lomax, *Tectonics* **13**, 561 (1994).
9. J. S. Namson and T. L. Davis, *Geol. Soc. Am. Bull.* **100**, 257 (1988).
10. J. McCarthy and P. E. Hart, *U.S. Geol. Surv. Open-File Rep. 93-301* (1993).

11. T. M. Brocher and M. J. Moses, *ibid. 93-276* (1993); T. M. Brocher and D. C. Pope, *ibid. 94-156* (1994).
12. R. M. Stewart and L. Peselnick, *J. Geophys. Res.* **82**, 2027 (1977).
13. J. M. Luetgert, *U.S. Geol. Surv. Open-File Rep. 88-238* (1988); C. Zelt and R. B. Smith, *Geophys. J. Int.* **108**, 16 (1992).
14. J. E. Ewing and M. Talwani, *J. Geophys. Res.* **96**, 6423 (1991); K. D. McIntosh, D. L. Reed, E. A. Silver, A. S. Meltzer, *ibid.*, p. 6459; A. S. Meltzer and A. R. Levander, *ibid.*, p. 6475; A. M. Trehu, *ibid.*, p. 6493; K. C. Miller, J. M. Howie, S. D. Ruppert, *ibid.* **97**, 19,961 (1992); J. M. Howie, K. C. Miller, W. U. Savage, *ibid.* **98**, 8173 (1993).
15. B. M. Page and T. M. Brocher, *Geology* **21**, 635 (1993).
16. T. M. Brocher, M. J. Moses, S. D. Lewis, *U.S. Geol. Surv. Prof. Pap.*, in press.
17. Reconnaissance refraction profiling in the San Francisco Bay Area was also interpreted in terms of a similar, simple two-layer crust by J. P. Eaton [*J. Geophys. Res.* **68**, 5789 (1963)], J. H. Healy [*J. Geophys. Res.* **68**, 5777 (1963)], and J. P. Eaton, *Calif. Div. Mines Geol. Bull.* **190**, 419 (1966). Constraints on the velocity and thickness of the lower crustal layer, however, were extremely limited from this earlier work, and no precritical reflections from it were obtained.
18. M. Liu and K. P. Furlong, *J. Geophys. Res.* **97**, 4941 (1992).
19. R. J. McLaughlin, W. P. Elder, K. McDougall, in *Geologic Excursions in Northern California: San Francisco to the Sierra Nevada*, D. Sloan and D. L. Wagner, Eds. (*Spec. Publ.* **109** California Divison of Mines and Geology, Sacramento, 1991), pp. 45–53.
20. R. C. Jachens, C. W. Roberts, A. Griscom, *Eos* (Fall Suppl.) **74**, 221 (1993).
21. A. W. Walter and W. D. Mooney, *Seismol. Soc. Am. Bull.* **72**, 1567 (1982); G. S. Fuis and W. D. Mooney, *U.S. Geol. Surv. Prof. Pap. 1515* (1990), p. 207.
22. R. H. Colburn and W. D. Mooney, *Seismol. Soc. Am. Bull.* **76**, 1305 (1986); W. S. Holbrook and W. D. Mooney, *Tectonophysics* **140**, 49 (1987).
23. K. P. Furlong and C. A. Langston, *Geophys. Res. Lett.* **17**, 1457 (1990).
24. P. A. Reasenberg and R. W. Simpson, *Science* **255**, 1687 (1992); K. P. Furlong and D. Verdonck, *U.S. Geol. Surv. Prof. Pap.*, in press; R. W. Simpson and P. A. Reasenberg, *ibid.*
25. I. G. Wong, R. W. Ely, A. C. Kollmann, *J. Geophys. Res.* **93**, 7813 (1988); J. P. Eaton, and M. J. Rymer, *U.S. Geol. Surv. Prof. Pap. 1487* (1990), p. 97.
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Redistribution of Intracellular Ca^{2+} Stores During Phagocytosis in Human Neutrophils

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Subcellular gradients of cytosolic free Ca^{2+} concentration, $[Ca^{2+}]_i$, are thought to be critical for the localization of functional responses within a cell. A potential but previously unexplored mechanism for the generation of gradients of $[Ca^{2+}]_i$ is the accumulation of Ca^{2+} stores at the site of Ca^{2+} action. The distribution of the Ca^{2+} store markers Ca^{2+}-dependent adenosine triphosphatase and calreticulin was investigated in resting and phagocytosing human neutrophils. Both proteins showed an evenly distributed fine granular pattern in nonphagocytosing cells, but became markedly concentrated in the filamentous actin–rich cytoplasmic area around the ingested particle during phagocytosis. This redistribution began at early stages of phagocytosis and did not depend on an increase in $[Ca^{2+}]_i$. Thus, accumulation of Ca^{2+} stores in a restricted area of the cell may contribute to the generation of localized increases in $[Ca^{2+}]_i$.

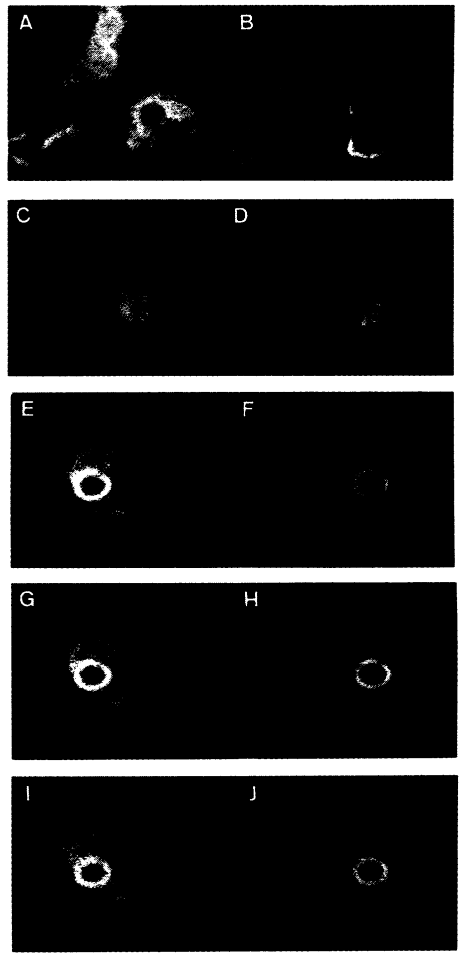

Fig. 1. Distribution of Ca^{2+}-ATPase (**A**, **C**, **E**, **G**, and **I**) and F-actin (**B**, **D**, **F**, **H**, and **J**) in resting and phagocytosing human neutrophils. Cells were purified as described (*4*) and allowed to adhere to glass slides and to phagocytose heat-killed yeast particles (*Saccharomyces cerevisiae*) that had been previously fixed to the slide (*20*). Each panel shows the rhodamine fluorescence (Ca^{2+}-ATPase) on the left and fluorescein fluorescence (F-actin) on the right. (A and B) Adherent nonphagocytosing neutrophils. (C and D) A neutrophil in the early stages of phagocytosis. Circles indicate the position of the yeast particle. (E through J) Three 1-μm-thick confocal serial sections through the top (E and F), center (G and H), and bottom (I and J) of the same neutrophil after completion of phagocytosis. The examples shown are typical of a total of 24 cells from a total of four experiments.

The control of $[Ca^{2+}]_i$ is crucial for the regulation of cellular activity. In many cellular systems, focal, rather than generalized, changes in $[Ca^{2+}]_i$ occur, presumably serving to localize functional responses within the cell (*1*). Examples of Ca^{2+}-mediated localized responses include release of neurotransmitters from synaptic terminals (*2*), target cell lysis by cytotoxic T lymphocytes (*3*), and phagolysosome fusion in neutrophils (*4*). Localized changes in $[Ca^{2+}]_i$ can be generated by local increases in the concentration of the Ca^{2+}-releasing second messenger inositol triphosphate (IP_3) or by local activation of receptor-mediated Ca^{2+} influx. An alternative or additional mechanism, however, might be an accumulation of intracellular Ca^{2+} stores. In neutrophils, processing of phagocytosed microorganisms requires a focal activation of Ca^{2+}-dependent cellular functions (*5*). Because particle ingestion can be initiated at any part of the cell surface, localization of $[Ca^{2+}]_i$ increases by accumulation of Ca^{2+} stores would necessitate a rapid directed transport of these stores to the site of phagocytosis.

We tested the hypothesis that Ca^{2+} storage organelles accumulate at sites of Ca^{2+} action during phagocytosis in human neutrophils. Filamentous (F) actin distribution was monitored in parallel as a marker of the remodeling of the contractile machinery. Markers for Ca^{2+} stores include the Ca^{2+}-dependent adenosine triphosphatase (Ca^{2+}-ATPase) SERCA2b

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