Upwelling Asthenosphere Beneath Western Arabia
and Its Regional Implications

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Two distinct phases of continental magmatism are evident in western Arabia. The first, from about 30 to 20 Ma, produced tholeiitic-to-transitional lavas emplaced along NW trends. The second, from about 12 Ma to Recent, produced transitional-to-alkaline lavas emplaced along N-S trends. The older phase is attributed to passive-mantle upwelling during extension of the Red Sea Basin, whereas the younger phase is attributed to active-mantle upwelling but was facilitated by minor continental extension perpendicular to plate collision. The younger magmatic phase is largely contemporaneous with a major period of crustal uplift to produce the West Arabian Swell after about 14 Ma. A variety of evidence suggests that the West Arabian Swell is thermally supported by hot, upwelling asthenosphere. In contrast to the distinct asymmetry of uplift and magmatism on opposing sides of the Red Sea Basin, these processes were symmetric across a N-S line marking the central axis of the West Arabian Swell. This axis coincides with two fundamental features: the Ha’il-Rubbah Arch in the north, and the Makkah-Madina-Nafud (MMN) volcanic line in the south. The symmetry of magmatism is demonstrated by petrochemical evidence that the MMN harrats were derived by greater degrees of partial melting, at shallower depths, than those harrats lying to the west and east of the MMN line. The potential temperature of the asthenosphere is estimated to be about 1436°C beneath the MMN line and about 1354°C beneath the flanking, more undersaturated harrats. The source of upwelling is either a mantle plume centrally located beneath the West Arabian Swell or an elongated and extended lobe of hot asthenosphere emanating from the Ethiopian mantle plume. Convective flow may have been channeled along a preexisting, regional flexure in the continental lithosphere which concentrated hot asthenosphere beneath the central axis of the Afro-Arabian Dome. This crest of mantle upwelling underlies the MMN line in the north and the Danakil Depression and Ethiopian rift system in the south. It also passes through the Red Sea Basin at the midpoint of an unusual, doubly propagating rift system where axial seafloor spreading began 4-5 m.y. ago. The NW trend of the Red Sea Basin was well established by crustal attenuation during the older magmatic phase. The Pliocene invasion of this basin by a N-S zone of mantle upwelling has resulted in seafloor spreading parallel to the preexisting structure along a rift system that has continued to propagate away from its eccentric mantle source in two opposing directions.

INTRODUCTION

The geographic association of uplift, rifting, and magmatism at the Afar triple junction provides a visual impression consistent with continental rifting at the crest of a plume generated dome [Cloos, 1939; Gass, 1970; Burke and Dewey, 1973; Senor and Burke, 1978]. An active role for the mantle in the genesis of the Red Sea and Gulf of Aden rifts, however, has received little support from the field data. Kinematic models suggest that these oceanic rifts were initiated by tectonically induced extension involving a passive mantle [Cochran, 1981, 1983; Courtillot et al., 1980; Courtillot, 1982; Bohannon and Eittreim, 1991]. Such a model is supported by a variety of studies that test the relative timing of uplift, rifting, and magmatism throughout the Red Sea and Afar regions [Schmidt et al., 1983; Schmidt and Hadley, 1984; Aboad, 1986a, b; Behre, 1986; Bohannon et al., 1989; Omar et al., 1989; McGuire and Bohannon, 1989; Bohannon and McGuire, 1990; Jarrige et al., 1990; Plaziat et al., 1990; Camp and Roobol, 1991a]. Whereas these investigations reveal a lack of evidence for plume generated uplift and erosion preceding the main period of rifting and magmatism in the late Oligocene and early Miocene (from about 30 to 20 Ma), they reveal a variety of evidence in support of a major period of postrift uplift that began in the mid-Miocene and has continued to the Present.

Fission track data on crustal apatites from the southeastern Red Sea coast show that the rate of uplift was accelerated after about 14 Ma, although it may have been initiated as early as 20 Ma [Bohannon et al., 1989]. An accelerated period of uplift in the mid-Miocene is consistent with the widespread deposition of mid-Miocene boulder conglomerates along the flanks of both the Red Sea and Gulf of Suez depressions [Schmidt and Hadley, 1984; Jarrige et al., 1990] and with the deposition of massive evaporite deposits in the deeper parts of the Red Sea graben, indicating a regression of the mid-Miocene Red Sea after about 14 Ma [Gillsma, 1968; Bayer et al., 1988]. Here we present evidence that this period of uplift has continued into the Holocene, contemporaneous with continental magmatism related to the upwelling of hot asthenosphere beneath western Arabia. In examining the geologic record of western Arabia, we attempt to resolve the variable character of continental magmatism and its conspicuous asymmetry east of the Red Sea Basin (Figure 1). We attribute the current physiography of Arabia and adjacent Africa to a two-stage model involving both the passive- and active-mantle hypotheses of Senor and Burke [1978]. Although we support the contention of others for passive-mantle rifting of the Red Sea Basin between about 30 and 20 Ma [e.g., McGuire and Bohannon, 1989],
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IAL-RUTBAH ARCH

THE MMN LINE

HA'IL-RUTBAH ARCH

HADAN

100 0 200 km

OLDER HARRATS

YOUNGER HARRATS

DIKES (-20-25 Ma)

Fig. 1. Distribution of Cenozoic volcanic rocks in western Arabia and adjacent Africa. Only the harrat lava fields of the older group, related to Red Sea extension in the Oligo-Miocene, are labeled. Harrats of the younger group, related to active-mantle upwelling in concert with plate collision, are labeled in Figure 4.

1989], our intent is to demonstrate that the subsequent period of contemporaneous uplift and magmatism was controlled by active-mantle upwelling concentrated along an axis that lies eccentric to the Red Sea Basin but coincident with the central crest of the Afro-Arabian Dome.

TWO STAGES OF CONTINENTAL MAGMATISM

The continental magmatic rocks in Saudi Arabia can be divided into older and younger groups which differ in their overall composition and structural setting (Figure 1) [Almond, 1986a, b; Coleman and McGuire, 1988; Camp and Roobol, 1991a]. As described below, these groups appear to reflect separate magmatic phases, contemporaneous with the two tectonic phases described above.

Radiometric age determinations from 182 localities in Saudi Arabia reveal an age range of 30-20 Ma for the majority of the older group (with a peak between 24 and 21 Ma) and an age range from 12 Ma to Recent for the younger group (Figure 2). Sporadic ages between 20 and 12 Ma appear to record a period of volumetrically insignificant volcanism. The older magmatic series in Saudi Arabia is generally contemporaneous with the voluminous Trap Series basalts in Yemen (41 analyses in Figure 2) and Ethiopia [Civetta et al., 1978; Zanettin et al., 1980; Mohr, 1983; Chiesa et al., 1988; Mohr and Zanettin, 1988].

In Saudi Arabia, the older rocks are tholeiitic to transitional, and most were emplaced along northwest trending structures parallel to the Red Sea Basin; in contrast, the younger rocks are transitional to strongly alkaline and were emplaced along northerly trending structures which diverge from the Red Sea trend by about 25° (Figures 1 and 3). (There are only two exceptions to the older and younger trends in Saudi Arabia. Harrat Hadan was extruded during the older period of magmatism above a north trending fissure which appears to overlie north trending structures in the Precambrian basement, whereas Harrat Nawasif/Boqum was the only harrat extruded from a northeast trending vent system.) Although the two groups have fundamentally different chemical signatures, they do not form distinct assemblages, as shown by their overlapping compositions on the total alkali versus silica diagram (Figure 3).

The older period of Red Sea extension is recorded in numerous northwest trending normal faults, dikes, intrusive complexes, and basaltic vent systems along the entire eastern margin of the Red Sea Basin (Figure 1) [Blank, 1977; Stenitz et al., 1978; Coleman et al., 1983; Pallister, 1987; Coleman and McGuire, 1988; Baldridge et al., 1991; Sebai et al., 1991; du Bray et al., 1991]. Several rift flank lava fields (harrats) and harrat remnants related to this period of extension are still preserved
Fig. 2. Compilation of radiometric ages for lava fields, intrusions, and volcanic interbeds east of the Red Sea in Saudi Arabia (182 determinations) and Yemen (41 determinations). For K-Ar age determinations greater than 5 Ma, only those with radiogenic argon greater than 10% are compiled as a test of reliability. (a) Range of determinations reported for individual lava fields, volcanic formations, and intrusive groups. (b) Composite histogram of reported ages east of the Red Sea. Data compiled from Civetta et al. [1978], Arno et al. [1980a, b], Coleman et al. [1983], Capaldi et al. [1987], Pallister [1984, 1987], Chiesa et al. [1988], Camp and Rooool [1989], du Bray et al. [1991], Sebai et al. [1991], and Camp et al. [1991, 1992]. The compilation does not include age data from the northern part of the Arabian continental basalt province, beyond the northern latitude of the Red Sea at 28°N; nor does it include those age determinations older than 35 Ma noted by Pallister [1987] and Brown et al. [1989].

immediately east of the Red Sea escarpment. These volumetrically small harrats include As Sarat (31-22 Ma [du Bray et al., 1991]), Hadan (about 27.5 Ma [Sebai et al., 1987, 1991]), and probably the uplifted Harrats Ishara and Harairah which are not well limited by K-Ar age determinations (Figures 1 and 2). These harrats are the most "alkalic" of the older magmatic series, although none possesses the strongly alkaline character of the majority of the younger harrats.

The younger magmatic series is composed entirely of harrat lava fields (about 85% of the total harrat volume) distributed...
Fig. 3. Total alkali versus silica diagram for 742 analyses of the older and younger magmatic phases from Yemen, Saudi Arabia, and Jordan. Field boundary is from Irvine and Baragar [1971]. The older group of 198 analyses includes 14 from the Yemen Traps [Chiesa et al., 1988], 122 from dikes, gabbroic-to-granitic plutons, and granophyres [Capaldi et al. [1987], 30 analyses; Pallister [1987], 11 analyses]; Coleman and McGuire [1988], 81 analyses), 41 from Hatrat As Sarat [du Bray et al., 1991], six from the Sita volcanics [Pallister, 1987], six from Harrat Hadan [Arno et al., 1980a], and nine from Harrat Ishara (V.E. Camp and M.J. Roobol, unpublished data, 1992). The younger group of 544 analyses includes 27 from the Recent Yemen volcanics [Civetta et al., 1980], 19 from Harrat Al Birk [Arno et al., 1980b], six from Harrat Nawasif/Boqum [Arno et al., 1980a], seven from Harrat Kurama (V.E. Camp and M.J. Roobol, unpublished data, 1992), 12 from Harrat Shamah [Barberi et al., 1980], 22 from Harrat Kura [Camp et al., 1991], 108 from Harrat Kishb [Camp et al., 1992], and 343 from Harrats Rahat, Khaybar, and Ithnayn (the MMN volcanic line) [Camp and Roobol, 1989; Camp et al., 1991]. The younger group of harrats can be further divided into mildly alkaline and strongly alkaline lava fields as demonstrated in Figure 5a.

SYMMETRY OF UPLIFT AND MAGMATISM

Dixon et al. [1989, 1991] attributed the asymmetry of magmatism across the Red Sea Basin (Figure 1) to a north trending zone of mantle upwelling which was present beneath western Arabia about 30 million years ago, but is now centered beneath the Red Sea spreading center due to the lateral migration of the overlying lithosphere. Whereas we agree with the existence of such a zone, we think that it is a much younger feature which was not involved in the Oligo-Miocene period of Red Sea rifting, as they propose [Camp and Roobol, 1991a]. Here we examine evidence that continental uplift and magmatism have been contemporaneous and symmetric across a linear, north-south axis of mantle upwelling over the past 12-14 m.y.

The West Arabian Swell

An asymmetric depositional facies pattern in the northern Red Sea led Bayer et al. [1988] to conclude that the northeastern Red Sea margin was uplifted above sea level after 14 Ma, and that this was shortly followed by renewed subsidence of the Egyptian offshore area at about 12 Ma. This age of uplift appears to be consistent with the post-14 Ma age recognized by Bohannon et al. [1989] along the southeastern Red Sea margin. The continuation of Arabian uplift into the Plio-Pleistocene has resulted in a topographic asymmetry across the present Red Sea Basin, which is generally coincident with the post-12 Ma magmatic asymmetry discussed above. We herein refer to this broad region of uplift and magmatism as the West Arabian Swell.

Although there is a steady south to north decrease in elevation on both sides of the Red Sea, mountain peaks along the Red Sea escarpment are consistently higher on the Arabian side than on the African side [Voggenreiter et al., 1988; Bohannon et al., 1989; Martinez and Cochran, 1989; Dixon et al., 1989]. More significant, however, are the inland regions which are less affected by rift shoulder uplift. West of the Red Sea, the African inland region is relatively flat, with an average elevation of about 500 m. In contrast, the Arabian inland region (the West Arabian Swell) is a broad, undulating tableland with average elevations of 1000-1500 m [Bohannon et al., 1989], similar to the crests of the other magmatically active, nonrifted swells in North Africa [Crough, 1983]. The average width of
the West Arabian Swell is about 1200 km, which is identical to that of the Hawaiian Swell [von Herzen et al., 1982], and in the middle range of oceanic swell widths listed by White and McKenzie [1989].

The West Arabian Swell forms the northern part of the much larger Afro-Arabian Dome, the dimensions of which are most recently defined by Almond [1986a] (modified in Figure 4). Almond [1986a] notes that this broad region of late Tertiary uplift lies far beyond the Red Sea margins and has an overall north-south axis which deviates from the Red Sea trend by about 25°, parallel to most of the post-12 Ma harrat linear vent systems. The southern crest of this domal anticlinorium lies along the SW trending Ethiopian Rift System, and the northern crest lies along the central N-S axis of the West Arabian Swell (Figure 4).

In contrast to the asymmetry of late Tertiary uplift and magmatism across the Red Sea Basin, there appears to be a symmetry of these processes across the central axis of the West Arabian Swell. This axis contains two significant features: the Makkah-Madinah-Nafud (MMN) volcanic line in the south [Camp et al., 1989] and the Ha'il-Rutbah Arch in the north [Brown, 1972; Greenwood, 1973] (Figure 4). The MMN volcanic line is defined by north trending, slightly en echelon linear vent systems which mark the central axes of Harrats Rahat, Khaybar, and Ithnayn; it extends over a north-south distance of more than 600 km, and it has been the major site of volcanism in Saudi Arabia over the past 10 m.y. The Ha'il-Rutbah Arch, aligned on strike north of the MMN volcanic line (Figure 4), has apparently been the site of several periods of uplift that preceded the most recent period of uplift described above. Late Cretaceous uplift appears to have continued into the the Early Tertiary, as indicated by the lack of Eocene deposition across its crest, and by the thickening of Eocene strata on both sides away from its crest [Powers et al., 1966; Greenwood, 1973; Riddler et al., 1986]. At least some uplift across the arch appears to have been contemporaneous with

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Fig. 4. Area of the Afro-Arabian dome (hatched line) and distribution of the post-12 Ma volcanic rocks in Arabia and adjacent Africa. The Afro-Arabian dome is modified after Almond [1986a] to include the Ha'il-Rutbah Arch in the north, which was an important site of Tertiary uplift [Brown, 1972; Coleman et al., 1983]. Almond [1986a] uses the sea level contour of the base of the Mesozoic [Brown, 1972] to partly delineate the dimensions of the dome in Arabia. The approximate distribution of the post-12 Ma volcanic rocks is from Eyal et al. [1981], Coleman et al. [1983], Mohr [1983], Almond [1986a], Camp and Roobol [1989], and Camp et al. [1991, 1992].
Miocene basalt extrusion of Harrat Shamah (Figure 4). Although basalt flows in Wadi Sirhan, immediately west of the main body of Harrat Shamah, are interbedded with Miocene shallow marine sediments, farther east they rest unconformably upon eroded lower Tertiary marine sediments at 700-800 m above sea level [Coleman et al., 1983].

Strongly Alkaline Magmatism on Opposing Sides of the Mildly Alkaline MMN Volcanic Line

Of the post-12 Ma lava fields on the West Arabian Swell, mappable petrochemical stratigraphies have been established for Harrats Rahat (circa 10 Ma to Recent), Kura (circa 10 to 5 Ma), Khaybar (circa 5 Ma to Recent), Ithnayn (circa 3 Ma to Recent), and Kishb (circa 2 Ma to Recent) [Camp and Roobol, 1989, 1991b; Camp et al., 1991, 1992; Roobol and Camp, 1991a, 1991b]. Although the remaining post-12 Ma harrats have been studied in less detail, reconnaissance sampling provides an adequate data base to assess their overall composition and the trend of fractionation [Arno et al., 1980a, b; Barberi et al., 1980; Civetta et al., 1980; Coleman et al., 1983; Coleman and McGuire, 1988].

The published analytical data reveal two distinct magma series for the post-12 Ma volcanic rocks. One is clearly undersaturated with abundant normative nepheline, whereas the other is transitional with both nepheline-normative and hypersthene-normative rock types. The undersaturated series is primarily composed of alkali olivine basalt (AOB) and basanite which fractionate to phonolite. The transitional series is primarily composed of olivine transitional basalt (OTB) and subordinate AOB which fractionate to trachyte and comendite. The undersaturated series contains a significant volume of ultramafic xenoliths (generally entrained in basanite), whereas the transitional series has a distinct lack of xenoliths.

The well-established petrochemical stratigraphy for the MMN harrats and for Harrat Kura to the west and Harrat Kishb to the east provides cross-sectional petrogenetic data on the asthenospheric source beneath the West Arabian Swell. The overall alkaline (undersaturated) chemical composition of Harrats Kura and Kishb are typical of most of the other Arabian harrats. In contrast, Harrats Rahat, Khaybar, and Ithnayn are the only post-12 Ma harrats in Saudi Arabia and Jordan of the transitional series. It is significant that these three transitional harrats, primarily composed of OTB (>60% of total volume) with subordinate AOB and hawaiite (Figure 5), are restricted to the central portion of the West Arabian Swell along the MMN volcanic line.

The overall difference in the chemical composition of the MMN harrats is attributed to greater degrees of partial melting. The degree of partial melting from a peridotite source should be reflected in the Zr/Nb ratios of the derivative lavas. Since the distribution coefficient for Zr in clinopyroxene is about 10 times larger than that for Nb [Dunn and McCullam, 1982; Watson and Ryerson, 1986], higher Zr/Nb ratios indicate greater degrees of partial melting from mantle peridotite [Alther et al., 1988]. From 68 representative harrat samples from Saudi Arabia, Alther et al. [1990] demonstrate that the largest Zr/Nb ratios are from the MMN line (Harrat Rahat) and that the smallest ratios are from harrats located the farthest to the west (Uwayrid) and east (Hutaymah) of the MMN line. Although there is little evidence for a systematic variation in this reconnaissance data, it is clear from our data (Figure 6) that the MMN lavas have significantly higher Zr/Nb ratios reflecting overall greater degrees of partial melting than Zr/Nb values for the more alkaline lavas from Harrat Kura to the west and Harrat Kishb to the east.

Experimental studies on the derivation of basaltic magmas at high pressures [O'Hara and Yoder, 1967; Kushiro, 1969; Walker et al., 1979; Stolper, 1980; Sack et al., 1987] suggest that there is a positive correlation between depth and alkali content. Thus the flanking more alkaline harrats may also have been derived from a slightly deeper asthenospheric source than the less alkaline MMN harrats. A somewhat deeper source for the flanking harrats appears to be consistent with the rare earth data. Increasing light rare earth element (LREE)/heavy rare earth element (HREE) ratios which are greater than those of the OTB lavas that dominate the MMN harrats [Camp and Roobol, 1989; Camp et al., 1991, 1992]. These different ratios are unlikely to simply reflect variations in crystal fractionation because (1) many of the chondrite-normalized REE patterns cross in the MREE range, and (2) the analyzed lava types have similar Mg numbers (Mg# = Mg/[Mg + Fe2+]).

Coleman et al. [1983] show that basalt analyses from Harrat Khaybar and Harrat Al Birk (Figure 4) lie along parallel and separable trend lines reflecting low-pressure (< 40 km) and high-pressure (> 40 km) fractionation paths, respectively, on the diopside-olivine-silica plot of Walker et al. [1979]. This suggests that the inferred shallower depths of melting beneath the MMN line may correspond with shallower depths of fractionation, as well.

We conclude that the MMN harrats were derived by greater degrees of partial melting, at shallower depths. From evidence below we attribute the greater degrees of partial melting to a hotter mantle source beneath the MMN line and the shallower depth of melting to a coinciding crest of mantle upwelling, the generalized symmetry of which is shown schematically in Figure 7.

Melt Generation

McKenzie and Bickle [1988] define the heat content of the mantle by its potential temperature $T_p$, the temperature it would have if brought to the surface adiabatically without melting. The normal $T_p$ of asthenosphere to produce mid-oceanic ridge basalt (MORB), as calculated by McKenzie and Bickle [1988], is 1280°C with a range of ±30°C. Using this temperature as a reference point, we consider three possible models for melt generation beneath the West Arabian Swell: (1) decompressional partial melting of normal temperature asthenosphere, with $T_p = 1280°C$ [e.g., Foucher et al., 1982], (2) decompressional partial melting of metasomatized subcontinental lithosphere, with $T_p < 1280°C$ [e.g., Bailey, 1987; Bonatti, 1990; Pearce et al., 1990], and (3) partial melting of hot asthenosphere, with $T_p > 1280°C$ [e.g., White and McKenzie, 1989]. Melt generation in all three models must take place under adiabatic conditions.

Decompressional Partial Melting of Asthenosphere with $T_p = 1280°C$

McKenzie and Bickle [1988] show that the amount of magma produced during crustal extension depends largely on the $T_p$ of the asthenosphere and the stretching factor of the
Although stretching of this magnitude appears to be consistent with decompressional partial melting during the 30-20 Ma period of magmatism and Red Sea extension [e.g., Cochran, 1983; Coleman and McGuire, 1988], it is clearly inconsistent with the post-12 Ma period of intraplate volcanism based on the lack of evidence for significant extension. Buried fissures beneath the N-S linear vent systems provide evidence for negligible stretching across the width of the West Arabian Swell since the mid-Miocene. On a more local scale, however, extension and subsidence along the MMN line are demonstrated by higher mountain peaks to the west and east and by a basin-and-range topography beneath Harrat Rahat having maximum graben depths of about 300 m below the harrat surface [Blank and Sadek, 1983]. From these data, we calculate a localized maximum stretching factor of only 1.018 across the MMN line. Extension of even very thin continental lithosphere cannot generate melting of normal $T_p$ asthenosphere unless the stretching factor is greater than 2 [McKenzie and Bickle, 1988]. A stretching factor of this magnitude above normal $T_p$ asthenosphere should result in subsidence of about 1.75 km, and even small degrees of extension would result in at least some subsidence as long as normal $T_p$ asthenosphere is present [White and McKenzie, 1989]. The combination of very minor stretching and significant uplift in western Arabia since the mid-Miocene appears to rule out a simple model of decompressional partial melting of normal $T_p$ asthenosphere by crustal extension.

Uplift and partial melting of normal $T_p$ asthenosphere could conceivably occur if there was some other mechanism, besides extension, for the adiabatic rise of asthenosphere to
Partial Melting of Metasomatized Lithosphere with \( T_p < 1280^\circ C \)

In contrast to the large degrees of crustal stretching required to melt normal \( T_p \) asthenosphere, only small degrees of stretching by melting may be required to melt metasomatized mantle containing low-temperature mineral phases. Pearce et al. [1990] propose such a model for partial melting beneath the Karacaldağ lava field on the northern Arabian plate.

Large domains of metasomatized mantle must be restricted to the subcontinental lithospheric mantle, well above the vigorously convecting asthenosphere [Fütter, 1987]. Pressure estimates on mantle xenoliths show that the subcontinental lithosphere beneath western Arabia occurs between 60 and 40 km; many of these xenoliths also provide petrologic evidence of metasomatism [McGuire, 1988a, b; Thonber, 1990; Henjes-Kunst et al., 1990; Nasir, 1992]. A very large volume of metasomatized peridotite, however, would be required to generate the volume of basalt seen at the surface and the supposed volume of basalt trapped at the crust/mantle boundary. Partial melting of such a source would also require an improbable linear zone of more fusible material beneath the MMN volcanic line to account for the observed symmetry and linearity of partial melting. Perhaps the best argument against such a source comes from the two-pyroxene equilibration temperatures for the mantle xenoliths, between 900\(^\circ\) and 1100\(^\circ\)C [Thornber and Pallister, 1985; McGuire, 1988a; Henjes-Kunst et al., 1990; Nasir, 1992], which are too cool for significant fusion of enriched peridotite. The evidence suggests that partial melting of metasomatized lithosphere with \( T_p < 1280^\circ C \) is also an unlikely model for melt generation beneath western Arabia.

Partial Melting of Hot Upwelling Asthenosphere with \( T_p > 1280^\circ C \)

The progressively higher elevations of the West Arabian Swell to the south, toward the Afar triple junction, suggest that uplift in Arabia may be largely a thermal response related to mantle upwelling centered in the Afar region. The adiabatic rise of asthenosphere with \( T_p = 1280^\circ C \) would require a greater amount of upwelling to produce the observed uplift than would the rise of asthenosphere with \( T_p > 1280^\circ C \). As shallow levels near the crust-mantle boundary. Given a dry peridotite solidus, McKenzie and Bickle [1988] show that significant melting of asthenosphere with a \( T_p \) of 1280\(^\circ\)C probably cannot occur below about 50 km. This would require an unusually large magnitude of adiabatic upwelling, which clearly cannot be attributed to crustal extension. Without a reliable mechanism for considerable upwelling, partial melting of asthenosphere with \( T_p = 1280^\circ C \) appears to be an unlikely model for magma generation beneath western Arabia.

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Fig. 6. Variation in Zr/Nb for the MMN harrats (Rahat, Khybar, and Ithnayn) and the flanking Harrats Kura and Kishb. The only MMN harrat samples with low Zr/Nb ratios, similar to those from Harrats Kura and Kishb, are a few high-MgO hawaiites located at the northern end of the MMN volcanic line on Harrat Ithnayn (shaded region).

Fig. 7. Map showing the distribution and density of harrat vents on the West Arabian Swell, and their proposed spatial relationship to mantle upwelling. The generalized symmetry and morphology of mantle upwelling are based on variations in the relative depth and degree of partial melting across the MMN volcanic line (see text).
described above, it is difficult to envisage a reliable mechanism for significant rise of normal temperature asthenosphere into the lithosphere. Alternatively, we examine here evidence for heating and thinning of the lithospheric mantle by the rise of asthenosphere having elevated $T_p$.

Heating and thinning of lithospheric mantle. Geophysical data provide some evidence for elevated mantle temperatures beneath western Arabia. Voggenreiter et al. [1988] note that there is an asymmetry in the Bouger gravity field across the Red Sea Basin, with the Arabian side having values of -110 mGal and the Egyptian side having values of -80 mGal [Izzoldine, 1982, 1987]. They interpret these data as evidence that the lithosphere on the Arabian side is on average less dense and hotter. They conclude that the somewhat asymmetric heat flow profiles of Martinez and Cochran [1989] for the northern Red Sea may also imply a hotter lithosphere beneath Arabia, and this appears to be consistent with the evidence of Bayer et al. [1988] for asymmetric uplift of the Arabian side of the northern Red Sea after about 14 Ma.

Not all geophysical data support the idea a hotter lithosphere. Surface heat flow over western Arabia is cooler than the world average [Gettings, 1981; Gettings et al., 1986] and projects to a temperature of about 400°-500°C at 40-50 km depth [McGuire and Bohannon, 1989]. This projected temperature range, however, is at variance with the 900°-1100°C range calculated from the mantle xenolith data, at the same depth [Thornber and Pullister, 1985; McGuire, 1988a; Henjes-Kunst et al., 1990; Nasir, 1992]. This discrepancy suggests that the thermal gradient of the upper mantle is not in equilibrium with that at the surface, and McGuire and Bohannon [1989] interpret this disequilibrium relationship as evidence that asthenospheric upwelling beneath western Arabia is younger than 20 Ma. This appears to be consistent withapatite fission track data suggesting a mid-Miocene age of uplift [Omar et al., 1989; Bohannon et al., 1989].

McGuire and Bohannon [1989] note that the calculated mantle-xenolith temperatures are high for their depth beneath shield rocks and must therefore represent a regional elevation of the mantle temperature. A regional perturbation of the thermal gradient should result from thinning of the lower lithosphere, as its mantle portion is converting to asthenosphere by thermal erosion. A thinned lithospheric mantle seems reasonable from the xenolith data. Pressure-temperature estimates on xenoliths from Harrat Uwayrid led Henjes-Kunst [1989] to suggest that the asthenosphere-lithosphere boundary in that region is at a shallow depth of about 60 km. McGuire and Bohannon [1989] estimate the asthenosphere-lithosphere boundary beneath Harrat Kishb to be at a depth of about 75 km. Both estimates imply a significant amount of thermal erosion of the lower lithosphere by hot upwelling asthenosphere. Attherr et al. [1990] come to a similar conclusion based on low $^{143}$Nd/$^{144}$Nd ratios for Arabian harrat lavas which suggest the incorporation of a lithospheric mantle component into asthenosphere-derived magmas.

Variations in the depth and temperature of upwelling asthenosphere. The projection of a best fit geotherm passing through the Harrat Kishb xenolith data, led McGuire and Bohannon [1989] to estimate the temperature of the asthenosphere at the base of the lithosphere beneath Harrat Kishb to be 1400°C at depth of about 75 km. Although this P-T estimate is not well constrained, it is consistent with model calculations on the degree of partial melting for the harrat lavas. McKenzie [1984] shows that isentropic melting at this temperature and pressure would produce a partial melt fraction of about 3.7%, which is close to Rayleigh law calculations of partial melting for the basanite average composition from Harrat Kishb. In contrast, the OTB lavas of the MMN volcanic line were derived by partial melting of at least 10%, as determined from Rayleigh law calculations [Camp and Roobol, 1989; Camp et al., 1991] and experimental investigations on similar rock types [Myers and Kushiro, 1977; Jaques and Green, 1980]. If we assume a crest of mantle upwelling beneath the MMN line at a depth of about 60 km, then a temperature of about 1475°C is required to produce a melt fraction of 10% [McKenzie, 1984]. The derivation of larger melt fractions would require even greater mantle temperatures.

The asthenosphere temperatures calculated above equate to potential temperatures of about 1354°C beneath Harrat Kishb and 1436°C beneath the MMN volcanic line. Although these values are meant to be gross approximations, they lie significantly above the 1280°C potential temperature of normal convecting asthenosphere, and within the range of elevated potential temperatures associated with mantle hot spots [White and McKenzie, 1989].

The mid-Miocene to Recent harrats above the West Arabian Swell are extensive (>80,000 km²) but thin and of small total volume (probably <10,000 km³). Their small volume is consistent with field evidence for minor crustal stretching since the mid-Miocene, even if one considers their generation to have involved high asthenosphere temperatures and a thin lithosphere. For example, given the constraints of a 70-km-thick undisturbed continental lithosphere (the mechanical boundary layer of Parsons and McKenzie [1978]) above an asthenosphere with a potential temperature of 1480°C, McKenzie and Bickle [1989] show that a stretching factor of 1.1 will generate a melt thickness of only 1.5 km; given the same constraints, a stretching factor between 2 and 5 will generate between 10 and 20 km of melt. The smaller melt thickness is probably still greater than that generated beneath the MMN volcanic line. The larger melt thickness is similar to that produced at the highly extended intersection of the Red Sea, Gulf of Aden, and Ethiopian rifts near the site of the Afar mantle plume [Berkhemer et al., 1977].

McKenzie and Bickle [1989] demonstrate that melt generation beneath continents is an important contributor to crustal accretion, consistent with evidence that the base of the crust acts as a density trap for upwelling basaltic magmas [Cox, 1980; Stolper and Walker, 1980]. Given the very small stretching factor, it seems likely that harrat extrusion is only a small fraction of the total melt generated beneath the West Arabian Swell. This is consistent with petrologic data indicating that few, if any, of the harrat basaltic lavas are primary melts but rather are fractionated magmas derived from primary melts which accumulated in reservoirs near the base of the crust [Camp and Roobol, 1989; Camp et al., 1991]. The crystallization of basaltic magma at this depth is now reflected in igneous-textured xenoliths entrained in the harrat lavas [McGuire, 1988b].

A MODEL FOR THE CONCENTRATION OF HOT MANTLE ALONG A LINEAR, MIGRATING AXIS

The contemporaneity of uplift and magmatism since about 12 Ma (Figure 2) together with the above evidence for elevated mantle temperatures beneath western Arabia are consistent with the active-mantle hypothesis of Sengor and Burke [1978], which attributes thermal uplift and magmatism to the active
rise of anomalously hot asthenosphere. This hypothesis is only partly applicable, however, since melt generation in Arabia was also clearly facilitated by the development of north trending fractures on the uplifted lithosphere due to plate collision.

The West Arabian Swell has a width and elevation (1200 km and 1000 m) consistent with the hotspot model of White and McKenzie [1989]. They show that swells of similar size are thermally supported by narrow plumes which are deflected laterally by the overlying lithosphere to produce mushroom-shaped heads of anomalously hot mantle some 1500 km across. In its simplest form, however, this model does not resolve (1) the distinct linearity of volcanism along the MMN line or (2) the northward migration of MMN volcanism which began on southern Harrat Rahat at about 10 Ma, on Harrat Khaybar at about 5 Ma, and on Harrat Ithnayn at about 3 Ma. Since major rift-related structures are absent, the linearity of the MMN line cannot be simply attributed to decompressional partial melting above a linear rift zone, nor can the linearity and volcanic migration along this volcanic line be attributed to plate migration above a stationary plume because the northward movement of the Arabian plate is clearly incompatible with such a model.

Bayer et al. [1989] suggested that the asymmetric distribution of volcanic rocks east of the Red Sea could be attributed to the position of a regional hinge zone that occurs on the eastern side of the Red Sea and continues to the south along the East African rift zone. We concur with Bayer et al. [1989] and suggest that the linear morphology of mantle upwelling may be at least partly controlled by directed flow of asthenosphere beneath a preexisting flexure in the continental lithosphere.

The top of the Precambrian basement west of the Afro-Arabian Dome is essentially flat lying or dips slightly to the west, but to the east it dips by an average of about 10° to form the basement of the Zagros orogen in the north and the basement of the Somalia basin in the south [Bayer et al., 1989]. Emplacement of the Zagros and Oman nappes in the Late Cretaceous appears to have been contemporaneous with a major period of uplift along the Ha'il-Rutbah arch [Greenwood, 1973; Hancock et al., 1984; Riddler et al., 1986], so that the northern hinge line and eastern flank of Afro-Arabian Dome was at least partially developed prior to mantle upwelling in the Tertiary. To the south, the east dipping lithosphere of the Somali basin appears to be the result of Jurassic downwarping [Hutchinson and Engles, 1970; Beydoun, 1982], so that it was also present before Tertiary upwelling. The deflection of hot, rising asthenosphere against this regional lithospheric flexure would have modified the morphology of mantle upwelling, and we suggest that the N-S crest of upwelling now preserved beneath the MMN volcanic line in the south, and probably beneath the Ha'il-Rutbah Arch in the north, may be the result of such modification.
We propose two possible models for the hot asthenosphere source: (1) upwelling of a mantle plume centrally located beneath the West Arabian Swell or (2) convective flow emanating from the Ethiopian mantle plume to produce an elongated and extended lobe of hot asthenosphere beneath the West Arabian Swell. The similar uplift ages in Africa and Arabia would seem to support the second model, and convective flow away from the Afar region would be a convenient mechanism to explain the northward migration of volcanism along the MMN line as it is funnelled beneath the preexisting lithospheric flexure described above. An alternative explanation for this migration, consistent with both models, is to attribute it to the northward progression of fissure development resulting from torque imposed on the lithosphere by the counterclockwise rotation of the Arabian plate due to seafloor spreading in the Gulf of Aden. Such rotation is evident from the paleomagnetic data of Tarling [1970] and from the left-lateral sense of shear along the MMN line as indicated by its right-stepping en echelon vent segments (Figure 8) (see for example, the interpretation of similar en echelon vent segments from Kilauea [Ryan, 1988]).

The principal problem with the second model for the asthenosphere source is that it requires a northward asymmetry of convective flow away from the Ethiopian plume over a distance of about 2000 km to account for uplift and volcanism on the West Arabian Swell. This distance is about twice the radii of typical plume heads beneath oceanic swells [White and McKenzie, 1989]. The White and McKenzie model, however, is based on oceanic examples which form by the circular deflection of mantle plumes beneath horizontal, homogeneous oceanic lithosphere. It is unlikely that the such circular shapes would be maintained beneath heterogeneous, regionally deformed continental lithosphere [e.g., Thompson and Gibson, 1991], and for this reason, we do not entirely rule out the lateral migration of asthenosphere over such great distances. On the other hand, it is more difficult to explain how such migration could occur well beyond the confines of the Red Sea Basin which should have been a natural channel for upwelling.
asthenosphere. We are therefore inclined to favor a separate mantle source beneath the West Arabian Swell. In context of the East African Rift system, such a source could be considered the northernmost in a series of mantle plumes, analogous to those beneath the Kenyan and Ethiopian Domes.

A Comparison with Ethiopia

Both the West Arabian Swell and the Ethiopian Dome appear to be underlain by hot, upwellin mantle; these two regions differ, however, in some important respects. The >3000-m-high crest of the Ethiopian Dome has been the site of dramatic rifting and prolific eruptions of silicic ignimbrite [Mohr and Zanettin, 1988]. In marked contrast, the MMN line occurs at lower elevations, in a region of minor normal faulting, and sporadic silicic volcanism related to crystal fractionation processes [Camp and Roobol, 1989; Camp et al., 1991]. It seems clear that the thermal structure of the lithosphere differs beneath these two regions. This does not necessarily mean that Ethiopia is underlain by a hotter asthenosphere, however, since variations in lithospheric thicknesses, at constant asthenosphere $T_p$, can also account for the observed differences. We suggest that Ethiopia is underlain by a thinner subcontinental mantle and that the voluminous silicic eruptions near the rift reflect crustal anaxesis where the mantle lithosphere has been totally, or nearly, consumed by thermal erosion. The smaller degrees of uplift associated with the West Arabian Swell, together with the lack of evidence for major rifting and crustal melting along the MMN line, suggest a thicker lithosphere, possibly above an equally hot asthenosphere that has not yet penetrated the crust-mantle boundary.

Regional Implications

The hinge line recognized by Bayer et al. [1989] is equivalent to the Cenozoic axis the Afro-Arabian Dome (Figure 4). In Arabia this axis coincides with the Ha'il-Rutbah arch and the MMN volcanic line; in Africa it coincides with the high central region of the Ethiopian Dome and the southwest trending axis of the Ethiopian Rift System. Both the Arabian and African regions appear to have similar uplift ages related to the upwelling of hot asthenosphere concentrated along this central axis. Although it is not clear whether or not the West Arabian Swell and the Ethiopian Dome are underlain by separate mantle plumes, a genetic link between these two regions may be apparent along the connecting, middle portion of the axis. Here, the N-S strike line is the focus of two additional regions of well-known mantle upwelling (Figure 9): (1) it is coincident with the N-S axis of the magmatically active Danakil Depression and (2) it cuts across the southern Red Sea Basin at the site of axial seafloor spreading 4-5 m.y. ago.

The Red Sea

The Danakil Depression is separated from the MMN volcanic line by the Red Sea Basin. After a 10-m.y. period of passive extension related to the older magmatic phase, the Red Sea Basin was well established along a northeast trend by about 20 Ma. Below, we examine the proposed effect of the younger magmatic phase, when a zone of N-S mantle upwelling was superimposed discordantly across the Red Sea trend about 14 Ma.

There is a consensus of opinion that the Red Sea magnetic lineaments recognized by Roessler [1975] reflect oceanic crust produced by axial seafloor spreading over the past 4-5 m.y. Opinions on the generation of oceanic crust before this time, however, have been controversial [cf., Cochran, 1983; Girdler and Southern, 1987; Le Pichon and Gaulier, 1988]. Le Pichon and Gaulier [1988] argue that ocean floor accretion began in the Red Sea at about 12-13 Ma, contemporaneous with that in the Gulf of Aden [Cochran, 1981]. This age appears to be consistent with the initiation of uplift and harrat volcanism in western Arabia, as described above, and may reflect the arrival of a thermal anomaly beneath the entire Afro-Arabian Dome. If this thermal anomaly has a linear morphology, as it appears to have beneath the West Arabian Swell, then its intersection with the Red Sea Basin should be evident in the seafloor-spreading history.

We can ignore the debate on the initiation of seafloor spreading, by examining only the last 4-5 m.y. of known ocean floor accretion. Although recent intrusion of basaltic magma is evident at several sites along the entire length of the Red Sea axial depression [e.g., Cochran, 1983; Bonatti, 1985; Cochran et al., 1991], the continuous generation of oceanic crust along the axis over the last 5 m.y. can only be positively demonstrated in the southern part of the Red Sea [Roessler, 1975; Cochran, 1983] (Figure 9). Le Pichon and Gaulier [1988] argue for continuous seafloor spreading in the central and northern Red Sea, but this cannot be confirmed by the paleomagnetic data.

Both the nature of the crust and the style of extension prior to 5 Ma are irrelevant to the model we describe below; the model rests, however, on the assumption that the magnetic anomaly pattern described by Roessler [1975] and Cochran [1983] approximates the distribution of basalt generated by axial seafloor spreading in the southern Red Sea since about 5 Ma. Courtillot [1982] demonstrated that this period of seafloor spreading is unusual in that it has involved rift propagation in two opposing directions (to the northwest and southeast). He points out that the southeast direction of rift propagation is inconsistent with a simple asthenospheric source emanating from a large mantle plume centered at the Afar triple junction. At first glance, there appears to be no compelling reason why axial seafloor spreading should be restricted largely to the southern portion of the Red Sea since about 5 Ma, nor is there an adequate explanation for the peculiar style of rift propagation in two opposing directions.

The source for a doubly propagating rift system has to lie beneath the axial plane, between the two propagating rift ends. When the crest of asthenospheric upwelling beneath the MMN line is projected across the Red Sea into the Danakil Depression, its intersection with the Red Sea axis occurs at the initiation site of axial seafloor spreading 4-5 m.y. ago (Figure 9). We suggest that seafloor spreading may have begun with the invasion of this hot line into the previously attenuated Red Sea crust, which resulted in rift propagation in two opposing directions, away from the mantle source but parallel to the preexisting basin structure. In a departure from conventional models, we propose that the main asthenospheric source for Red Sea volcanism may lie eccentric to its axis and coincident with a north-south thermal line beneath the crest of the Afro-Arabian Dome (Figure 9).

Unlike the middle section of the Red Sea, which is characterized by normal MORB (N-MORB), the southern section is characterized by transitional MORB (T-MORB) and AOB similar in composition to oceanic island basalt [Altherr et al., 1988; Barrat et al., 1990]. Barrat et al. [1990] attribute this difference to the mixing of depleted MORB mantle with an enriched hotspot component in the southern Red Sea region. A comparison of incompatible element abundances for near-
primary alkalic basalts from the southern Red Sea and the MMN line (Figure 10) appears to indicate similar mantle source regions along this proposed zone of N-S upwelling.

Melting of hot asthenosphere at the site of rifting should normally result in a thickened crust from magmatic underplating due to the increase in melt production [White and McKenzie, 1989]. Seismic refraction studies, however, show that the crustal thickness beneath the Dahlak and Farsan Banks in the southern Red Sea is not greater (and perhaps much less) than about 10 km [Bohannon and Eittreim, 1991], as compared to the 7-km thickness of average oceanic crust [McKenzie and Bickle, 1988]. The lack of a substantially thickened crust in the southern Red Sea region may indicate a somewhat cooler asthenosphere (perhaps $T_p \lesssim 1380^\circ$C) than that present beneath the Ethiopian Dome in the south and beneath the MMN volcanic line in the north. This would tend to support the idea of a separate mantle plume beneath the West Arabian Swell.

**Discussion**

The Red Sea and Gulf of Aden basins are clearly the two most prominent regions of shallow asthenospheric upwelling in northeast Africa and Arabia. These two rift arms were well developed by 20 Ma as the result of tectonically induced passive rifting [Cochran, 1981, 1983] associated with the older period of tholeiitic to transitional magmatism (Figures 2 and 3). We suggest that a third, less prominent region of asthenospheric upwelling developed later, beneath the central crest of the Afro-Arabian Dome, where the active rise of hot asthenosphere has resulted in uplift associated with the younger period of transitional to strongly alkalic magmatism.

The central axis of the Afro-Arabian Dome extends across several distinct provinces. It maintains a north-south orientation from the Ha'il-Rutbah Arch through the MMN volcanic line and across the Red Sea Basin into the Danakil Depression, but then it turns to the southwest along the rifted crest of the Ethiopian Dome (Figure 4). At its intersection across each of these provinces there is petrological and structural evidence that this axis is coincident with a zone of upwelling asthenosphere. The symmetry of mantle upwelling on opposing sides of this thermal line is evident from (1) lavas derived by decreasing degrees of partial melting, at increasing depths, west and east of the MMN volcanic line, (2) the top of the Precambrian basement which decreases in elevation on opposing sides of both the Ha'il-Rutbah Arch and the general crest of the Afro-Arabian Dome, and (3) the doubly propagating rift system on opposing sides of the N-S line at its intersection with the Red Sea axis. The morphology and temperature gradient of mantle upwelling along this central axis may be similar to that portrayed in Figure 11, although the N-S extension of hot asthenosphere into western Arabia may or may not involve a separate mantle plume.
The younger period of magmatism in northeast Africa and adjacent Arabia has been dominated by two separate components of mantle upwelling: (1) deep upwelling of elevated $T_p$ asthenosphere beneath the central crest of the Afro-Arabian Dome, and (2) shallow upwelling of normal $T_p$ asthenosphere beneath the Gulf of Aden, and much less conspicuously, beneath the central and northern axial plane of the Red Sea Basin [Cochran, 1983; Bonatti, 1985; Cochran et al., 1991]. Asthenospheric upwelling beneath the southern part of the Red Sea axial plane appears to be a mixture of these two mantle components [Barrat et al., 1990].

The post-14 Ma transitional to strongly alkaline volcanic rocks of the Ethiopian Rift, the Danakil Depression, and the West Arabian Swell were generated by a deep, enriched source beneath the crest of the Afro-Arabian Dome; in contrast, the partly contemporaneous tholeiitic rocks in the Gulf of Aden and Afar regions were generated by a shallow, depleted source related to seafloor spreading. Whereas the static Ethiopian mantle plume is rooted in the deep mantle, the independent, convecting asthenosphere beneath the Gulf of Aden has migrated into the Afar region due to the westward propagation of the Sheba ridge spreading center [Cournilhet et al., 1980; Cochran, 1981; Courtillot, 1982].

The present configuration of the Afar triple junction is largely a consequence of the post-14 Ma superimposition of this two-component asthenospheric system (the younger magmatic phase) upon the previously developed Red Sea and Gulf of Aden basins (the older magmatic phase). Of the three rift arms comprising the triple junction, the Red Sea and Gulf of Aden rifts were well developed by 20 Ma as the result of passive-mantle rifting [Cochran, 1981, 1983]; in contrast, the Ethiopian rift did not develop until about 10 Ma [Kazmin and Berhe, 1978; Kohn et al., 1980], shortly after the initiation of significant crustal uplift along the crest of the Afro-Arabian Dome [Almond, 1986a, b; Bohannon et al., 1989]. The Ethiopian rift appears to be the only arm of the Afar triple junction which can unambiguously be considered the sole product of active-mantle upwelling, contemporaneous with active-mantle upwelling beneath the MMN line on the West Arabian Swell.

In our model, three limbs of upwelling asthenosphere are connected at the Ethiopian mantle plume (Figure 11). Although two coincide with the Ethiopian and Gulf of Aden rifts, the third limb of upwelling diverges from the Oligo-Miocene Red Sea Basin (Figure 11). The apparent shallow asthenosphere beneath the central and northern Red Sea Basin has been attributed to a passive mantle filling the voids of an extended crust [Cochran, 1983; Cochran et al., 1991]. We attribute seafloor spreading in the southern Red Sea to the Pliocene invasion of this extended crust by the north-south limb of rising asthenosphere described above. On this basis, we suggest that the southern Red Sea spreading axis may be a unique example of a doubly propagating rift system eccentrc to its zone of active-mantle upwelling.

Acknowledgments. This study is founded upon a project to map the Saudi Arabian harrats as part of the work program of the Saudi Arabian Directorate General of Mineral Resources (DGMR), Jiddah. The work is published with the approval of the Assistant Deputy Minister designate for Survey and Exploration at the DGMR, Mohammed Tawfiq, who thank for continued encouragement and support. We thank Bob Bohannon and Anne McGuire for thoughtful reviews and Kevin Burke and Peter Hooper for providing us with constructive comments on earlier manuscript drafts.


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(Received July 10, 1991; revised April 23, 1992; accepted April 23, 1992.)