CRUSTAL STRUCTURE AND TECTONICS OF THE IMPERIAL VALLEY REGION, CALIFORNIA

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ABSTRACT

The U.S Geological Survey conducted an extensive seismic refraction survey in the Imperial Valley region of California in 1979. This region included primarily the Imperial Valley proper and West Mesa. Forty shots fired at seven shot points were recorded by 100 portable seismic instruments at typical spacings of 0.5-1 km. More than 1300 recording locations were occupied, and more than 3000 usable seismograms were obtained.

We analyzed five refraction profiles, modeled an existing gravity profile across the Salton Trough, constructed a basement depth map, and produced a structure and tectonic summary map of the Imperial Valley region. Results are itemized:

1) The models for the refraction profiles have in common a sedimentary layer ($V_p = 1.8$-5.0 km/s), a "transition" zone ($V_p = 5.0$-5.65 km/s), a basement ($V_p = 5.65$ km/s in Imperial Valley, 5.9 km/s on West Mesa), and subbasement ($V_p = 7.2$ km/s, only well documented in Imperial Valley).
2) The sedimentary layer ranges in thickness along the axis of the Salton Trough from 3.7 km (Salton Sea) to 4.8 km (U.S.-Mexican border). On West Mesa it ranges from 0-3.5 km.
3) The "transition" zone is about 1 km thick in most places. In Imperial Valley, there are no marked velocity discontinuities in this zone between the sedimentary layer and basement. On West Mesa, however, there is a discontinuity at the top of this zone.
4) There are apparently two types of basement. On West Mesa, beneath 0-3.5 km of sedimentary rocks, basement is crystalline igneous and metamophic rocks. In Imperial Valley, beneath 5-6 km of sedimentary rocks (including the "transition" zone), basement is likely to be mostly lower-greenshist-facies metasedimentary rocks, based primarily on the smooth transition in character from sediment to basement arrivals, the low value of basement velocity, and the fact that deep (4 km) wells in the Valley penetrate only the upper part of the known Cenozoic stratigraphic column for the Salton Trough.
5) The subbasement, or lower crust, ranges in depth along the axis of the Salton Trough from 16 km (Salton Sea) to 10 km (U.S.-Mexican border). Gravity modeling indicates that this layer deepens and (or) pinches out beneath the bordering mesas and mountain ranges. Based on its high velocity and the presence of intrusive basaltic rocks in the sedimentary section in the Imperial Valley, the subbasement is thought to be a mafic intrusive complex similar to oceanic middle crust.
6) The Imperial Valley (and also East Mesa) is underlain by a geologic section consisting of sedimentary rocks, metasedimentary rocks, and mafic intrusive rocks, according to our interpretation, all of which are late Cenozoic in age. West of the Imperial Valley-East Mesa region, West Mesa and the Peninsular Ranges are underlain mostly by pre-Cenozoic crystalline rocks, as are the Chocolate Mountains, east of the Imperial Valley-East Mesa region. The boundary, or suture, between new and old crust is revealed on a basement depth map, as it is marked by prominent buried scarps, up to 5 km in relief. On the west, the suture follows roughly the east edge of West Mesa. It is crooked, composed of northerly- and northwesterly-trending segments. On the east, the suture is linear and northwesterly in trend, following the base of the Chocolate Mountains near the Salton Sea and the Sand Hills fault farther southeast.
7) Certain block motions can be inferred from the configuration of the suture between new and old crust. A block between the San Jacinto fault zone and Elsinore fault appears to have moved about 50 km northwestward from the Cerro Prieto spreading center, and a block between the San Jacinto fault zone and San Andreas fault appears to have moved 25-45 km northwestward from the Brawley spreading center. Spreading at the Brawley spreading center may be asymmetrical.

Thus, new crust is forming in the Salton Trough as rifting occurs: Mafic igneous rocks intrude the lower crust as the rift opens, and sedimentary rocks are deposited in the rift basin. Rifting and intrusion produce high heat flow, metamorphosing the sedimentary rocks to relatively shallow depth in the rift basin.

INTRODUCTION

In this paper we summarize the results of an extensive seismic-refraction survey of the Imperial Valley region, California, conducted in 1979. Detailed description of the data and documentation of the results are available in Fuis and others (1981, 1982, 1984) and Kohler and Fuis (1983, in preparation). We present here (1) velocity models for five seismic-refraction profiles crossing the Imperial Valley region at different azimuths, (2) a density model for an existing gravity profile across the region, using our seismic structure to provide new constraints, (3) a geologic interpretation of these models, (4) a basement depth map of the region, and (5) a structure and tectonic summary map of the region, from which block motions in the region can be inferred.

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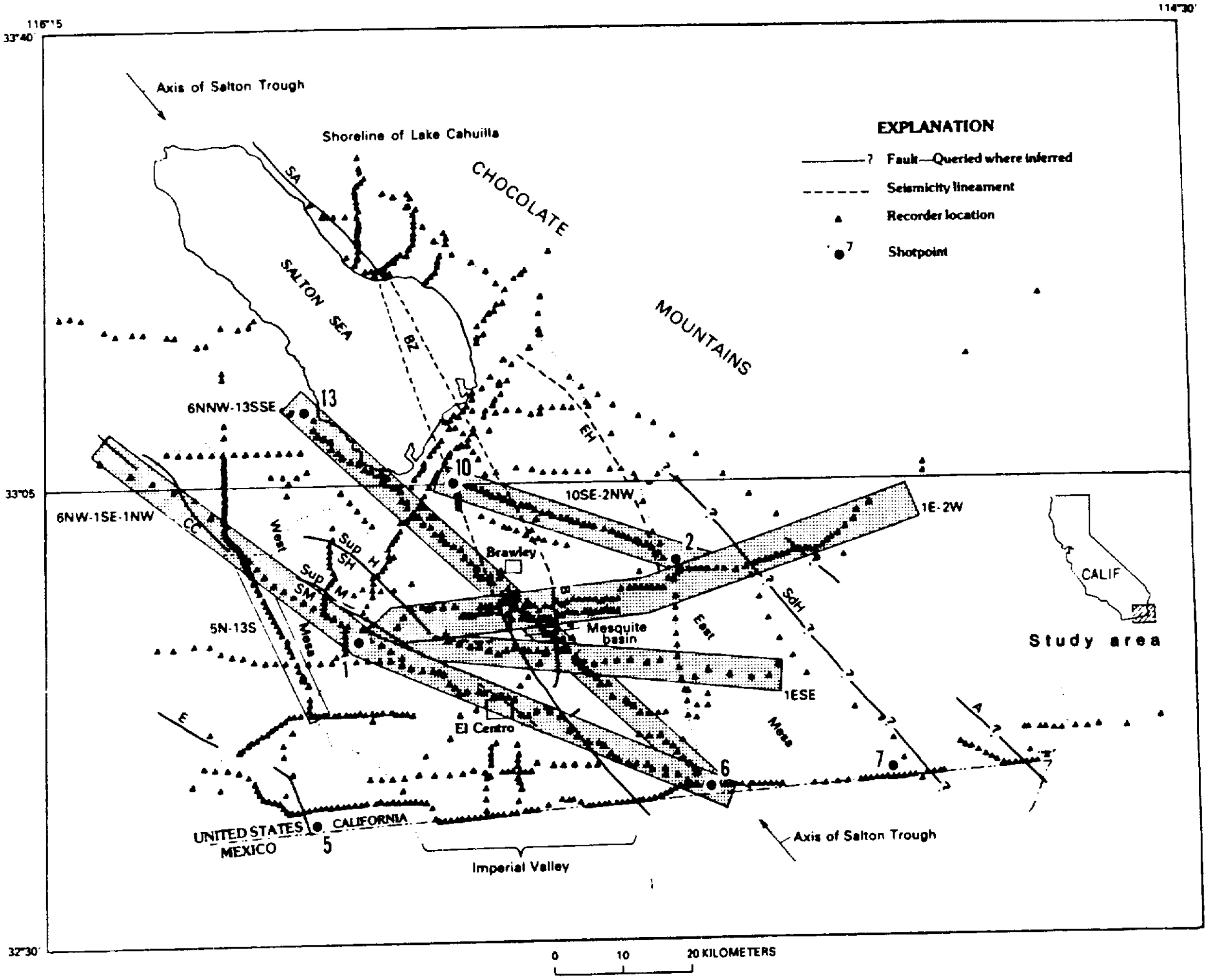

Figure 1. Locations of shot points, recorders, and refraction profiles analyzed. Profiles modeled are indicated by outline and stipple; profile segment 5N-13S, indicated by outline only, is discussed in text but not modeled. A, Algodones fault; B, Brawley fault zone; BZ, Brawley seismic zone (as defined by Johnson, 1979); CC, Coyote Creek fault; E, Elsinore Fault; EH, East Highline Canal seismicity lineament; I, Imperial fault; SA, San Andreas fault; SdH, Sand Hill fault(?); SH, Superstition Hills fault; SM, Superstition Mountain fault; Sup. H., Superstition Hills; Sup. M., Superstition Mountain.

We conducted our refraction survey primarily during the period January-March 1979 although some additional data was gathered following the October 1979 Imperial Valley earthquake. Our survey concentrated primarily on the Imperial Valley proper (the cultivated lowlands southeast of the Salton Sea) and West Mesa (the bordering mesa on the west) (fig. 1). During the primary survey, a total of 40 shots ranging in yield from 400 to 900 kg (1000-2000 lbs) of high explosive were detonated at 7 shotpoints (fig. 1). Each shot was recorded by 100 portable vertical-component seismic instruments (see Blank and others, 1979). On a typical shot night the instruments were arranged in a line or a pattern with instrument spacings of 0.5 to 1 km, and three shots were detonated. In all, more than 1,300 recording locations were occupied and more than 3,000 usable seismograms were obtained.

VELOCITY MODELS

Four reversed and one unreversed refraction profiles were analyzed. Seismic lines constituting a profile are given names such as 6NNW and 13SSE, which derive from the identification numbers of shot points from which the lines originate and the azimuths of the lines: NNW--north-northwest, SSE--south-southeast, and so forth. Profile 6NNW-13SSE lies along the axis of the Salton Trough, and profiles 6NW-1SE-1NW, 1ESE, 1E-2W, and 10SE-2NW cross the Trough at various azimuths (fig. 1). Velocity models for these profiles (fig. 2) were obtained by 2-dimensional raytracing; major results are itemized below:

1) All models have in common a sedimentary layer (Vp = 1.8-5.0 km/s), a "transition" zone (Vp = 5.0-5.65 km/s), a basement (Vp = 5.65 km/s in the Imperial Valley, 5.9-6.0 km/s on West Mesa), and subbasement (Vp = 7.2 km/s, clearly recorded only in the Imperial Valley). (Vp is compressional, or P-wave velocity.)

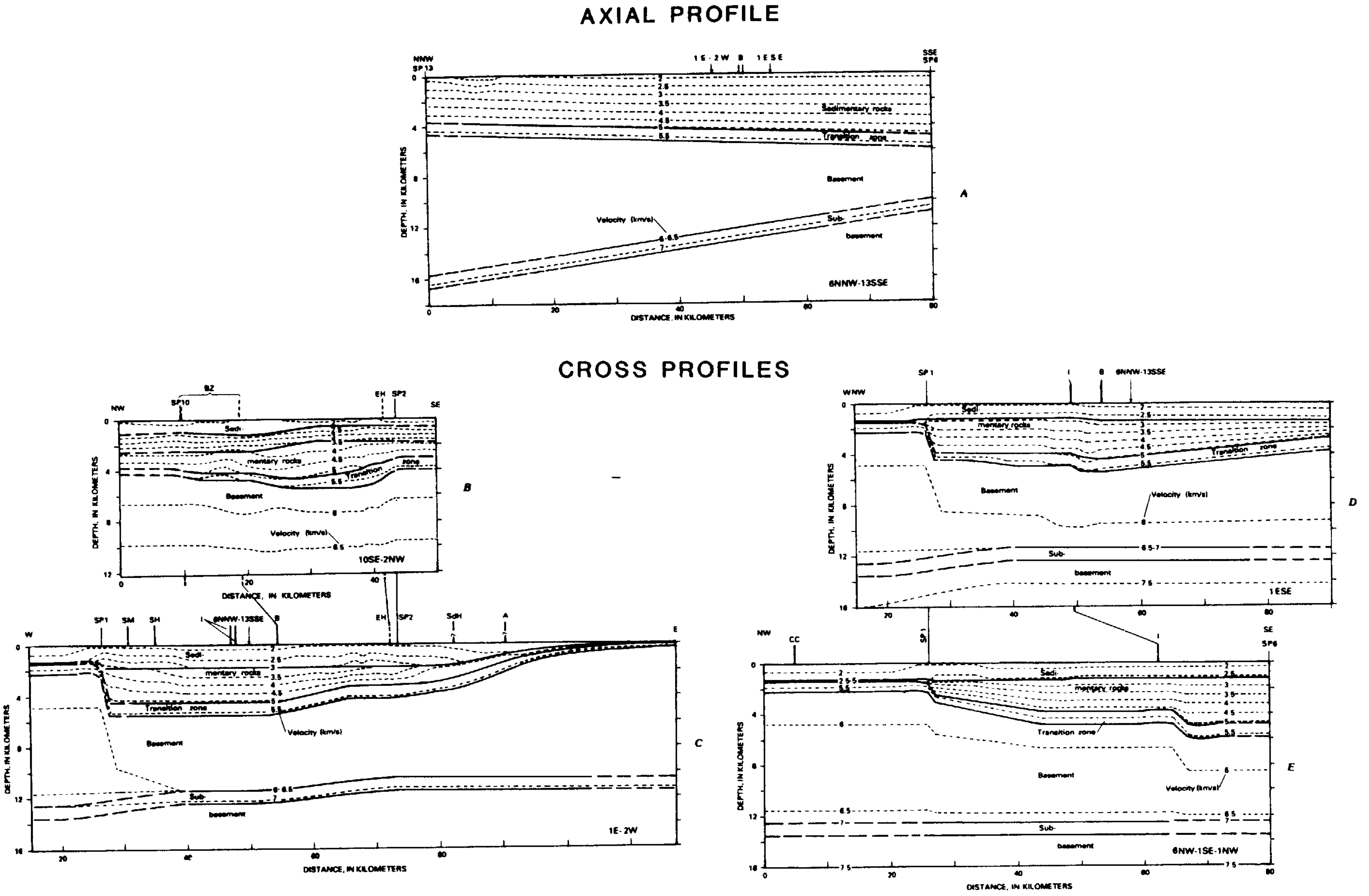

Figure 2. Velocity models for stippled profiles of fig. 1. Vertical exaggeration is 2x. Velocity boundaries (heavy lines, dashed where uncertain) are loci where velocity gradients can change but are not isovelocity lines. Light-dashed lines are isovelocity contours with values given in km/s; velocity-contour interval, 0.5 km/s. Shot points (SP) and geographic locations, are indicated at top, as well as fault traces, seismicity lineaments (abbreviated as in fig. 1) and and intersections of other profiles.

2) The sedimentary layer ranges in thickness along the axis of the Salton Trough from 3.7 km at the Salton Sea to 4.8 km at the U.S.-Mexican border (fig. 2a). On West Mesa it ranges from 0-3.5 km.

3) Velocity contours within the sedimentary layer dip to the southeast along the axis of the Trough (fig. 2a) and toward the axis of the Trough on cross profiles (fig. 2b-2e).

4) The "transition" zone is about 1 km thick in most places. In Imperial Valley, there are no marked velocity discontinuities in this zone between the sedimentary layer and basement. On West Mesa, however, there is a discontinuity at the top of this zone.

5) The upper basement has a velocity of about 5.65 km/s in the Imperial Valley, based on several reversed profiles (profiles 6NW-1SE-1NW, 1E-2W, 10SE-2NW, 6NNE-13SSW), but on West Mesa its velocity is about 5.9-6.0 km/s, based on a reversed-profile segment (profile segment 5N-13S, fig. 1) and a study by Hamilton (1970). The depth to basement ranges from 3.5 to 6.0 km in the Imperial Valley and commonly is in the range 4.5-5.5 km. On West Mesa the depth to basement ranges from 0-3.5 km (see discussion of basement depth map below).

6) Several structures are seen which affect the basement and transition zone boundaries as well as velocity contours within the sedimentary layer:

(a) A scarp extends along the Imperial fault from at least 12 km southeast of El Centro to about 9 km north-northeast of El Centro. It is down on the northeast, and its height apparently decreases from about 1 km at the southeast end of this interval (profile 6NW-1SE-1NW; fig. 2e) to less than 0.5 km at the northwest end (profile 1ESE; fig. 2d). A dip on the fault of about 68° NE fits the data at the southeast end, and a dip of 78° NE fits the data at the northwest end. No basement scarp was detected across the fault where it splays out farther north (see profile 1E-2W; fig. 2c). A northeast dip on the fault is consistent with the fact that earthquake epicenters locate northeast of the fault (Johnson, 1979), but a decrease in basement scarp height toward the north is opposite to the tendency of the surficial scarp, which increases in height toward the north (Sharp and Lienkaemper, 1982).

(b) An anomalous bump in the velocity contours is present in the lower section of the sedimentary layer about 10 km north of Brawley (profile 10SE-2NW; fig. 2b). This anomaly correlates with the so-called Brawley seismic zone, defined by Johnson (1979) to include the band of seismicity connecting the Imperial and San Andreas faults.

(c) A large scarp, down on the east, beneath shot point 1 is required because of the drastic difference in inferred depth to basement east and west of the shot point (profiles 6NW-1SE-1NW, 1ESE, 1E-2W; fig. 2c-2e). The precise height, shape, and location of this scarp is more uncertain than most features in the models. North of shot point 1, the scarp may be associated with the Superstition Mountain fault. South of the shot point, the scarp appears to be part of a buried north-south trending bench on the basement and transition zone that does not correlate with any structure mapped at the surface (see discussion of basement depth map below).

(d) There are no conspicuous basement scarps in the models along other mapped faults, although the Brawley fault zone, possibly the East Highline Canal seismicity lineament, and the Sand Hills and Algodones faults appear to correlate with changes in slope on the basement and transition zone (profile 1E-2W; fig. 2c).

7) An important discovery is the existence of a subbasement with a velocity of 7.2 km/s (near its top) at depths ranging from 10 to 16 km under the Imperial Valley. Evidence for this subbasement appears on all profiles longer than about 40 km. Modeling of both amplitudes and travel times of arrivals from the subbasement require that its velocity be considerably less than that of mantle. It can be modeled by a velocity discontinuity separating the lower basement (5.9-6.6 km/s) from the upper subbasement (6.6-7.0 km/s), at a depth range of 10-16 km. Below this discontinuity is a 1-km-thick zone of relatively rapid velocity increase to 7.2 km/s. Arrivals from a similar layer are reported by Hamilton (1970) for a profile in the Borrego Valley area, west of the Salton Sea. Hamilton calculated a velocity of 7.1 km/s and a depth of 14 km for this layer.

8) The topography of the subbasement, though of great importance to the structural framework for the Imperial Valley region, is difficult to resolve. An apparent dip of 4.5° NW is indicated in the model for profile 6NNW-13SSE (fig. 2a); however, depth to subbasement appears to decrease somewhat to the north in the models for profiles 6NW-1SE-1NW, 1ESE, and 1E-2W (fig. 2c-2e). The greatest disagreement is about 1 km and occurs at the intersection of profiles 6NNW-13SSE and 1E-2W. Thus we estimate our uncertainty in resolving depth to subbasement to be about 1 km. Combining our best information on depth to subbasement, we might plot only depths at the points for critical reflection on the different profiles. The picture that emerges is of a dome on the subbasement with its highest point 11 km deep in the region between Brawley and El Centro. This dome has a relief on its south side of a little more than 1 km, an amount barely resolvable, and on its north side of 5 km. Gravity modeling (see below) indicates an abrupt deepening of subbasement under West Mesa and a more gradual deepening under East Mesa. Thus the region of convergence of the Imperial and San Jacinto faults and the Brawley seismic zone appears to be a subbasement high, although we emphasize that the south closure on this dome is barely resolvable.

GRAVITY MODEL

The velocity structure derived from profiles 6NW-1SE-1NW and 1E-2W (fig. 2c, 2e) has been used to constrain an east-west gravity model across the Imperial Valley region. This model differs from previous ones (Kovach and others, 1962; Biehler and others, 1964; Plawman, 1978) in that it includes the newly discovered subbasement in this region.

A gravity profile across southernmost California taken from Oliver and others (1980) (fig. 3) shows that the central Imperial Valley is characterized by a negative Bouguer anomaly (-30 to -40 mGal), the Chocolate Mountains by a somewhat more strongly negative anomaly (-50 mGal), and the Peninsular Ranges by a strongly negative anomaly (up to -90 mGal). Therefore the Imperial Valley,

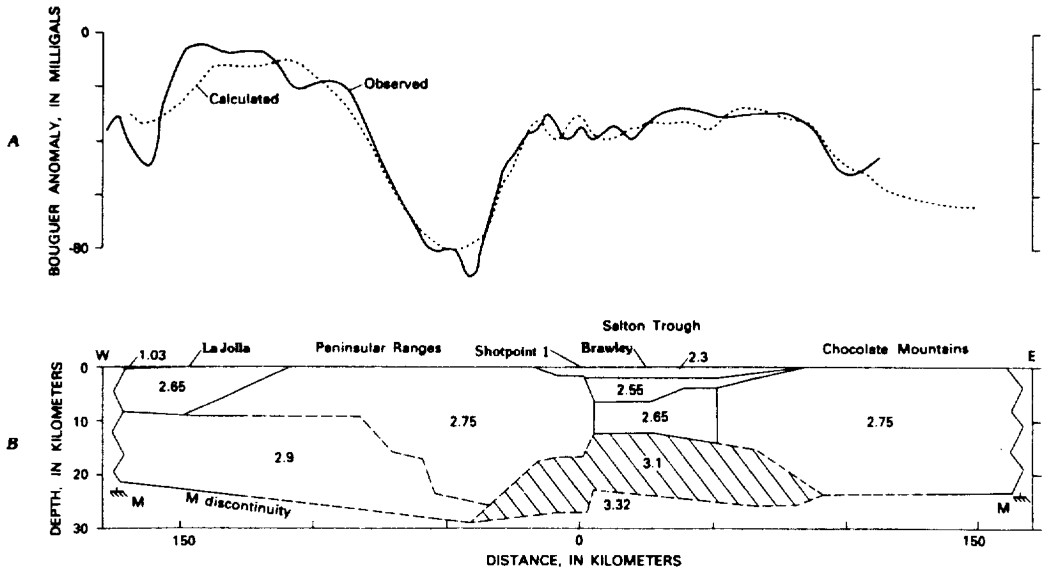

Figure 3. Cross section east-northeast across California from La Jolla to Chocolate Mountains. Gravity profile (a), taken from Oliver and others (1980); model (b); numbers are densities in Mg/m^3 (g/cm^3). Boundaries controlled by seismic refraction are solid; those adjusted to provide fit to gravity profile are dashed. Subbasement (lined area, density 3.1 Mg/m^3) beneath Salton Trough, absent in previous gravity models for Imperial Valley region, provides most of gravitational compensation for sedimentary rocks (densities 2.3 and 2.55 Mg/m^3) and inferred metasedimentary rocks (density 2.65 Mg/m^3).

despite its thick sedimentary layer, is a slight gravity high relative to the regions which flank it. Previous gravity models across the Valley have explained the lack of a negative anomaly by a mantle upwelling whose high density compensates for the light sedimentary layer. We here present a model in which the subbasement compensates for the sedimentary layer.

It is evident from the gravity model (fig. 3) that the subbasement (3.1 Mg/m^3) compensates gravitationally for both the sedimentary rocks (2.3 and 2.55 Mg/m^3) and the low-density basement (2.65 Mg/m^3) in the central Imperial Valley. The relatively flat gravity profile across the Salton Trough requires that the upper surface of the subbasement largely mirror the contact between the sedimentary rocks and basement. In particular, we note that the scarp on the basement near shot point 1 (fig. 3, distance 0 km) is mirrored on the subbasement (and also on the mantle). We also note that the negative anomalies over the Peninsular Ranges and Chocolate Mountains require that the subbasement deepen further and pinch out in those directions.

In our model, we show the mantle at a depth of about 23 km under the Imperial Valley and some variation in depth to mantle under the Salton Trough. These depths are not constrained by seismic data, and the current interpretation of the gravity data is not unique regarding depth to mantle or structure of the crust-mantle boundary.

Recent work by Lachenbruch (1983) has demonstrated that whereas densities and boundary shapes in our gravity model can be modified somewhat, our basic conclusion, that the subbasement mirror the shape of the sedimentary basin above it, still holds. Lachenbruch has gone further to show, however, that asthenosphere, or low-density mantle (3.20 Mg/m^3), can be brought up locally under the Salton Trough while still maintaining a fit to the observed gravity data. Asthenosphere would provide a source, through partial melting, for the mafic igneous rocks of the subbasement.

TWO TYPES OF BASEMENT

A plot of velocity versus depth for West Mesa and for the Imperial Valley proper illustrates the difference between basement in these two areas (fig. 4). On West Mesa there is a strong velocity discontinuity between the sedimentary rocks and the transition zone and a decrease in velocity gradient between the transition zone and the basement; upper basement has a velocity of 5.9 km/s. In the Imperial Valley, the sedimentary rocks blend smoothly, with a slight decrease in velocity gradient, into the transition zone, and the transition zone in turn blends, with another decrease in gradient, into the basement; upper basement has a velocity of 5.65 km/s. It is known from outcrops and wells that penetrate the sedimentary cover that basement on West Mesa is crystalline igneous and metamorphic rocks (Don Lande, oral commun., 1980; Dibblee, 1954). It is likely that the transition zone is merely a zone of weathering and open fractures near the surface of the crystalline basement (cf. Fuis, 1981). In the Imperial Valley, on the other hand, a number of lines of evidence indicate that basement is metasedimentary rocks. First, there is no velocity discontinuity between the sedimentary rocks and basement. Second, the low value of basement velocity, 5.65 km/s, is similar to laboratory velocities for sedimentary and low-grade metasedimentary rocks (see, for example, Stewart and Peselnick, 1977, 1978). Third, deep wells in Imperial Valley and on East Mesa penetrate only the upper part of the known Cenozoic stratigraphic

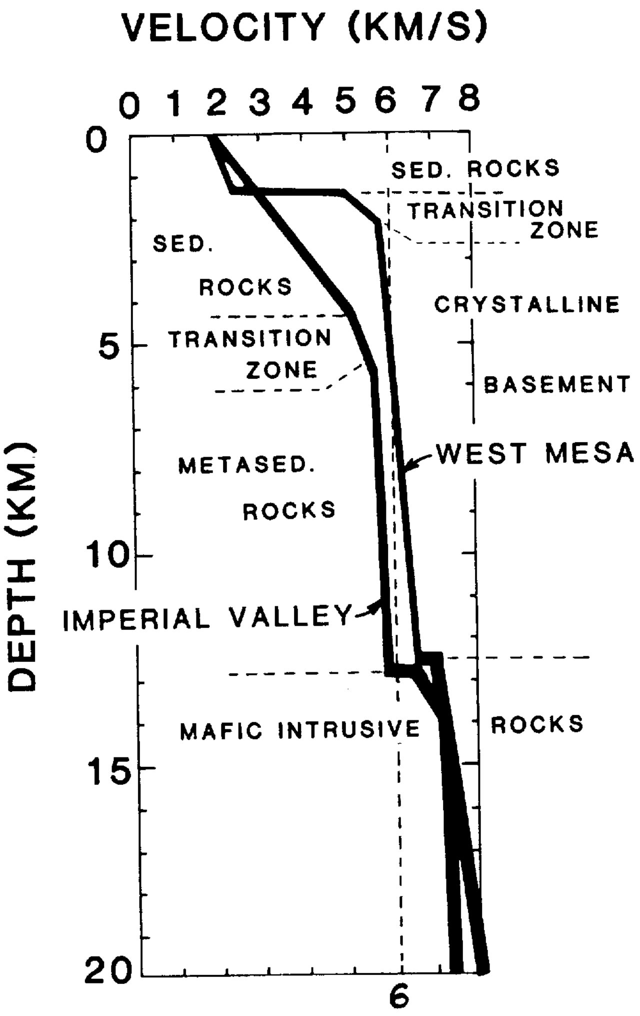

Figure 4. Velocity versus depth for Imperial Valley and West Mesa, with geologic interpretation. Curve for Imperial Valley is taken from center of velocity model for 6NNW-13SSE (fig. 2a), and curve for West Mesa was taken from northwest end of velocity model for 6NW-1SE-1NW (fig. 2e).

column for the Salton Trough, implying a considerable thickness of sedimentary rocks below. The deepest wells (4.1 km) penetrate to about the top of our transition zone, and thus it seems necessary that the transition zone and basement be primarily sedimentary and metasedimentary rocks. Fourth, outside of geothermal areas, temperature projections from deep wells indicate that the 300° C isotherm should be encountered at 5-7 km (see Fuis and others, 1984). Thus, one expects lower-greenschist-facies metamorphism at or near the depth to basement.

Contradicting our conclusion that basement in the Imperial Valley is metasedimentary rocks are granitic xenoliths in the Salton Buttes rhyolite extrusions. These xenoliths may indicate that remnants of crystalline crust are present in some parts of the Imperial Valley, but the xenoliths do not clearly resemble crystalline rocks in the Chocolate Mountains, on West Mesa, or in the Peninsular Ranges (see Robinson and others, 1976). Perhaps they derive from congealed magmas in the new crust.

The boundary between the crystalline basement on West Mesa and the inferred metasedimentary basement in the Imperial Valley is located at or near the prominent buried scarp beneath shotpoint 1 (see fig. 2c-2e), as velocity-depth curves change in this vicinity (see fig. 4). If we assume that this boundary, or suture, follows this prominent scarp in plan view, and if we assume that its counterpart on the east side of the Imperial Valley is also marked by a prominent scarp, then a basement depth map of the Imperial Valley region can provide valuable insight into local tectonics (see below).

SUBBASEMENT

A velocity of 7.2 km/s requires that the subbasement be mafic in composition, such as gabbro or amphibolite (see, for example, Birch, 1960). Basaltic xenoliths in the Salton Buttes rhyolite extrusions, and basaltic sills and dikes encountered in wells (see, for example, Griscom and Muffler, 1971) do indeed indicate the presence of mafic rocks at depth under the Valley. Presumably the subbasement, like this basalt, intrudes the basement. We suggest that the transition zone at the top of the subbasement consists of dikes and sills of (metamorphosed?) diabase or bodies of metagabbro, with velocities ranging from 6.6 to 7.0 km/s, and the lower part of the subbasement consists of gabbro with velocities of 7.2 km/s and higher. This inferred layering is similar to that of oceanic middle crust based on studies of ophiolites (see, for example, Clague and Straley, 1977; Salisbury and Christensen, 1978).

Our gravity modeling indicates that the subbasement, or lower crust, compensates largely for the thick section of relatively light sedimentary rocks in the Imperial Valley. Such modeling also indicates that this layer can not be mantle material, with a density as high as 3.3 Mg/m^3, as this material would produce an excessive gravity high over the Imperial Valley. Apparently this layer is being intruded to fill from below the continental rift represented by the Salton Trough, as sediment is being deposited to fill the rift from above. Lachenbruch (1983) has explained heat flow data in the Salton Trough using a model like this, involving underplating or distributed intrusion by mafic igneous rocks at or near the base of a thinning continental plate accompanied by sedimentation in a subsiding basin on top of the plate.

BASEMENT DEPTH MAP

A basement depth map (fig. 5) was constructed using "time-term" analysis of the refraction data, calibrated by model depths to basement (fig. 2), well data (fig. 6), and outcrop data (fig. 6). The reader is referred to Willmore and Bancroft (1960) for an explanation of the time-term method and to Kohler and Fuis (1983, in preparation) for application of this type of analysis to the Imperial Valley region. "Basement" refers to material with a velocity of 5.6 km/s or more. In general such velocities are encountered well below the surface, even on outcrops of crystalline rocks owing to open fractures and weathering. The average velocity of the basement determined from time-term analysis is

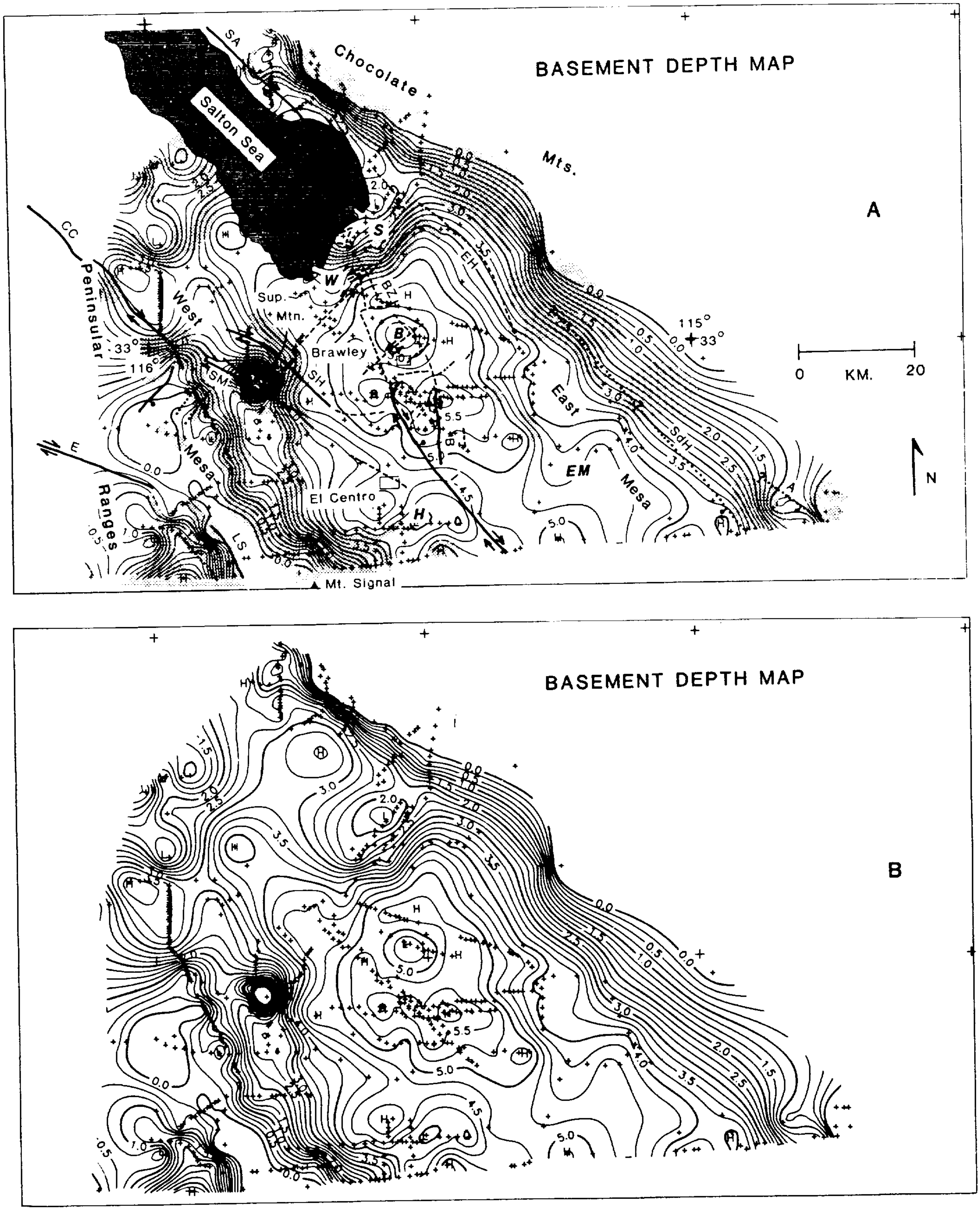

Figure 5. Basement depth map. (a) with and (b) without structural and geographic information. Numbers are depths (in km) to material with velocity greater than 5.6 km/s. Contour interval is 0.25 km. +'s are station-data points. Clear first arrivals from at least two shot points are required for each station-data point. Map is derived from time-term analysis of first-arrival data calibrated against model depths to basement (fig. 2), well data (fig. 6), and outcrops (fig. 6). Note that the 0.0 km contour interval does

Figure 5 continued.
not correspond perfectly to outcrops for two reasons: (1) Depth to 5.6 km/s material generally lies below surface, even on outcrops. (2) There is much scatter in data relating time-terms to near-surface basement. Note that contours are poorly controlled when distant from station-data points, such as in Salton Sea and along most of east flank of Imperial Valley. Heavy lines are faults judged to be important in Cenozoic tectonics of Salton Trough; dotted where concealed (compiled from Dibblee, 1954; Strand, 1962; Jennings, 1967; Mattick and others, 1973; Dillon, 1975; Plouff, 1976; Sharp and others, 1982). Dashed lines are seismicity lineaments (compiled from Johnson and Hutton, 1982; C.E. Johnson, written commun., 1981). Full arrows indicate historical sense of movement; for seismicity lineaments movement is inferred from focal mechanisms. Half arrows indicate geologically determined sense of movement. Faults and seismicity lineaments are abbreviated as in fig. 1. Stipple pattern indicates areas where slopes exceed 16 percent. Geothermal areas shown are those listed in Brook and others (1978) and Renner and others (1975) having reservoir temperatures exceeding 150° C: B, Brawley; EM, East Mesa; H, Heber; S, Salton Sea; W, Westmorland.

5.8 km/s, which is close to an average of velocities inside the Imperial Valley (5.65 km/s) and velocities on West Mesa (5.9-6.0 km/s).

The Imperial Valley region can be divided into three subregions based on basement depth and type; these are the West Mesa-Peninsular Ranges, the Imperial Valley-East Mesa, and the Chocolate Mountains-Yuma subregions. Basement depths in the West Mesa-Peninsular Ranges subregion range from 0 km on outcrops of granodiorite (for example, on Superstition Mountain), to more than 3.5 km in Lower Borrego Valley (just northwest of Superstition Mountain), underlain by Cenozoic basin fill. Basement on West Mesa is crystalline rocks in nearly all places, as discussed above. In the Imperial Valley-East Mesa subregion, basement depth ranges from less than 2.0 km to more than 5.5 km, and basement is inferred to be metasedimentary rocks in most places. Basement depths in the Chocolate Mountains-Yuma subregion range from 0 km to more than 2.0 km. Outcrops on this flank of the Salton Trough indicate that basement, as on West Mesa, is crystalline rocks, although different in composition. Rocks underlying the Chocolate Mountains-Yuma subregion include Precambrian metamorphic rocks (amphibolite-grade metasedimentary and metaigneous gneisses), Mesozoic intrusive rocks (dominantly quartz monzonites) and metamorphic rocks (the Orocopia schist) (see, for example, Dillon, 1975; Haxel, 1977). Rocks underlying West Mesa and the Peninsular Ranges, on the other hand, include Paleozoic to Mesozoic sedimentary and volcanic rocks and Mesozoic intrusive rocks (dominantly granodiorite) (see, for example, Dibblee, 1954; Todd and Shaw, 1979).

The three subregions we have defined are separated from one another on the basement depth map (fig. 5) by zones of high gradient, or scarps. The scarp separating the West Mesa-Peninsular Ranges subregion from the Imperial Valley-East Mesa subregion has a maximum relief of nearly 5 km and is quite crooked. It trends northwestward near Mount Signal, northward between Mount Signal and Superstition Mountain, northwestward again north of Superstition Mountain, and northward again along the west side of and under the Salton Sea (figs. 5, 6). (The reader is referred to the structure and tectonic summary map of the Imperial Valley region, fig. 6, where, for interpretive reasons, zones of high gradient, which are generally complex, have been replaced by linear scarps of different lengths.) Other zones of high gradient, or prominent scarps, in this subregion include (1) a scarp trending northwestward from Mount Signal, diverging from the north-south zone in this area, (2) an "embayment" in Lower Borrego Valley (just northwest of Superstition Mountain), bounded on the southwest by the Coyote Creek fault, and (3) an "embayment" in the southwest corner of the map, bounded on the northeast and north by the Laguna Salada and Elsinore faults. The diverging scarps north of Mount Signal, each commonly having a relief of 1.5-2 km, indicate that the crystalline basement under West Mesa is terraced.

The Imperial Valley-East Mesa subregion is separated from the Chocolate Mountains-Yuma subregion by a remarkably linear scarp with a relief that is commonly 4-5 km. This scarp is well controlled by refraction data northeast of the Salton Sea and also in the southeast corner of the map. In these locations the scarp is steep; in the southeast corner of the map it is also terraced. In the region between these two areas of good refraction control, the scarp is broader, but denser instrument coverage might have indicated it is also steep in this region. It appears most closely associated with the base of the Chocolate Mountains (see outcrops on the structure and tectonic summary map, fig. 6) and the inferred Sand Hills fault. The Algodones fault is clearly associated with the terracing in the southeast corner of the map. Within the Imperial Valley-East Mesa subregion, strong gradients are associated with the two largest geothermal fields, the Salton Sea and Heber fields. Both are outlined by northeast-trending gradients, and resemble "peninsulas" of shallow basement protruding into the Imperial Valley in opposite directions from the bounding scarps on either side of the Valley. The Salton Sea "peninsula" is bounded on the southwest by the Brawley seismic zone and on the southeast by a seismicity lineament that extends entirely across the Imperial Valley. The Heber "peninsula" is bounded on the northeast by the Imperial fault. The Brawley geothermal field is associated with a circular basement dome bounded on its east and west sides by seismicity lineaments of the Brawley seismic zone. The East Mesa geothermal field is also a "peninsula" of shallow basement extending southward from the bounding scarp on the northeast, but is of much lower relief than the features associated with the Salton Sea and Heber fields. The apparent shallowing of basement under the geothermal areas is presumably a complex phenomenon resulting in part from dike injection and a complex pattern of metamorphism. "Depth to basement" is thus presumably poorly defined in these areas. Other features in the Imperial Valley-East Mesa subregion include (1) a scarp along the entire length of the Imperial fault, reaching 1 km in height just north of the U.S.-Mexican border, (2) a scarp along the linear projection of the Superstition Mountain fault, coinciding with a

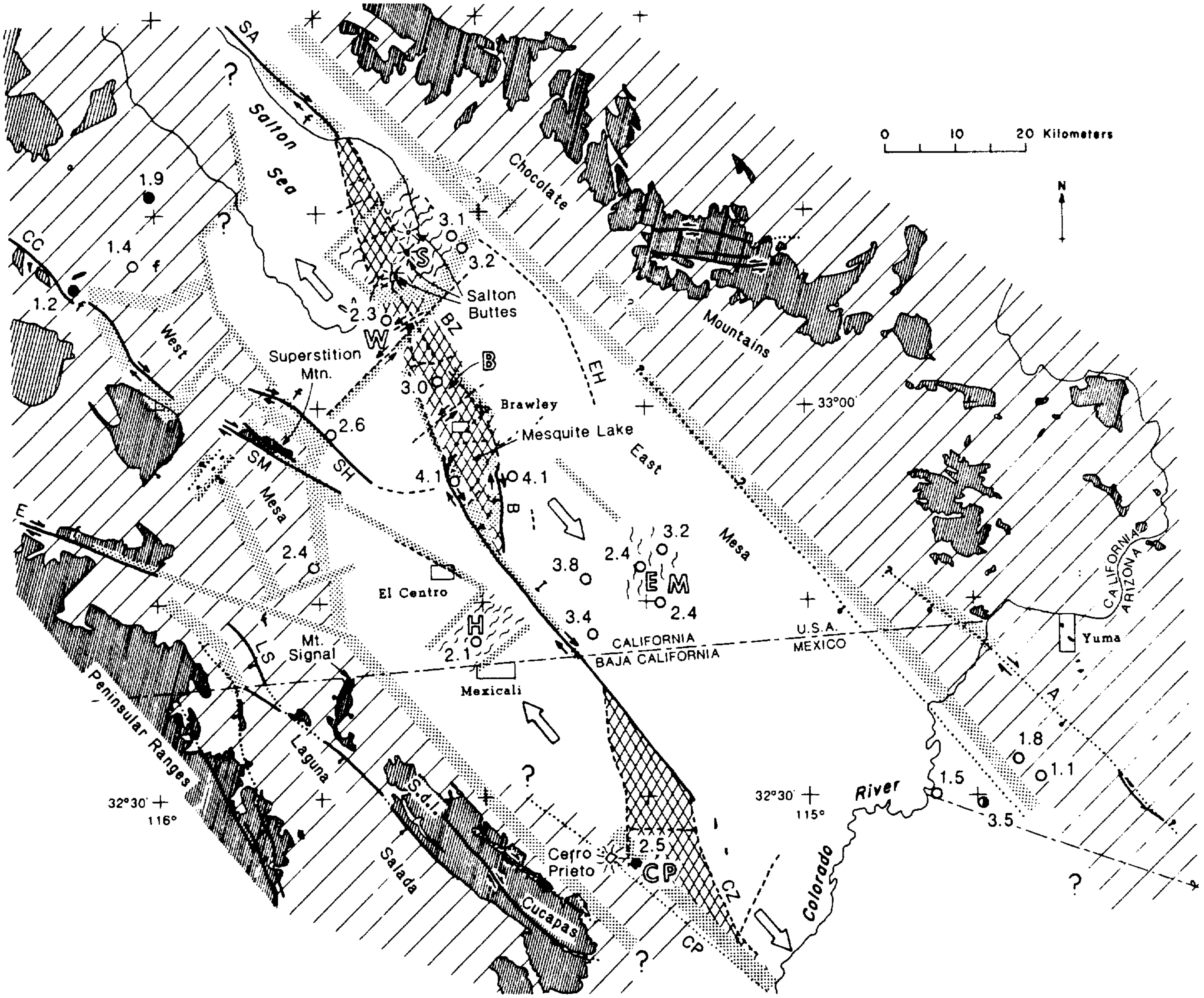

Figure 6. Structure and tectonic summary map. Zones of high (greater than 16 percent) gradient on basement depth map are indicated here by wide stippled lineaments of different lengths. Other selected linear features on basement depth map are indicated here by narrow stippled lineaments. Faults, seismicity lineaments, and geothermal areas are reproduced from fig. 5. "f" refers to areas of Cenozoic folding and (or) reverse faulting. Similar information in Mexico and southwest Arizona comes from Gastil and others (1971), Mattick and others (1973), Reed (1975), Johnson and Hutton (1982), James J. Lienkaemper (oral commun., 1984). Abbreviations in Mexico are CZ, Cerro Prieto seismic zone; CP, Cerro Prieto geothermal area and Cerro Prieto fault; S.d.l. Cucapas, Sierra de los Cucapas. Seismic zones are crosshatched. Apparent basement shallowing under Salton Sea, Heber, and East Mesa geothermal fields is indicated by wavey lines. Circles with numbers denote wells and depths in km. Solid circles penetrate crystalline rocks. Open circles penetrate only Cenozoic sedimentary rocks. Half-filled circle in Arizona penetrates numerous Miocene basaltic dikes(?) near base. Outcrops of pre-Cenozoic crystalline basement are indicated by closely spaced lines; locally include Tertiary intrusive rocks. Inferred extent of crystalline basement beneath Cenozoic sedimentary rocks is indicated by widely spaced lines, queried where there is little data. Direction of spreading from Brawley and Cerro Prieto spreading centers is indicated by large open arrows. See text for discussion.

seismicity lineament through El Centro, and (3) fainter scarps along the Brawley fault zone and San Andreas fault which change sense along strike. The scarp along the San Andreas fault is distinct from the much larger scarp associated with the base of the Chocolate Mountains, to the northeast.

STRUCTURE AND TECTONIC SUMMARY MAP

Nearly all faults expressed at the surface and many seismicity lineaments are associated with linear features and (or) strong gradients on the basement depth map, as discussed above. This association is illustrated on a structure and tectonic summary map (fig. 6) on which we show faults and seismicity lineaments, and represent strong gradients on the basement-depth map by scarps of different lengths. In addition, we compile all available information on the pre-Cenozoic crystalline basement in the region including outcrops and wells that penetrate to this basement. This structure summary is extended into Mexico and Arizona in order that some tectonic relationships become clear. The pronounced scarp just northeast of Mount Signal is extended southeastward along the base of the Sierra de los Cucapas in analogy with the scarp along the base of the Chocolate Mountains and is in accordance with well information in the Cerro Prieto geothermal field (Reed, 1975). The scarp associated with the Sand Hills fault is extended through southwest Arizona where well information indicates an abrupt thickening of Cenozoic sedimentary rocks to the southwest. The deepest well in this region, 3.5 km deep, penetrates no crystalline basement but does penetrate a Miocene andesite flow, and, near its base, Miocene basaltic dikes(?) (Eberly and Stanley, 1978; Joseph W. Kulik, written commun., 1984).

The areal extent of old crust beneath Cenozoic cover, indicated by widely spaced diagonal lines on the summary map (fig. 6), is inferred from outcrops, well data, and refraction results. On the west side of the Imperial Valley, the boundary, or suture, between new and old crust correlates with a prominent buried scarp. Velocity-depth curves differ on either side of this scarp (fig. 4), indicating juxtaposition of different crustal sections. We next make the assumption that the suture is everywhere marked by a scarp, and we use the basement depth map to follow the suture around in plan view. For example, we assume that the prominent linear scarp along the northeast flank of the Imperial Valley is the location of the suture on this side of the Salton Trough. Perhaps, however, the suture is not always associated with a scarp. Furthermore, the suture may not always be a clean vertical break, as we have shown it, but a stretched boundary of significant horizontal extent, such as one would expect from necking or thinning of a plate. The configuration of the suture that we show is undoubtedly an oversimplification and certainly a subject for further investigation.

Spreading centers are inferred on the structure and tectonic summary map (fig. 6) from seismicity, volcanism, and subsidence. The Brawley seismic zone and the seismic zone associated with the Cerro Prieto geothermal field are shown in a crosshatched pattern. Both zones are spindle shaped and connect active strike-slip faults (see Johnson and Hutton, 1982). Holocene volcanism is seen at the Salton Buttes in the Brawley seismic zone (Robinson and others, 1976) and at Cerro Prieto in the Cerro Prieto geothermal field (Reed, 1975). Mesquite Lake is an active depression between the Imperial fault and Brawley fault zone (Sharp and Lienkaemper, 1982), and an active depression is also forming at the north end of the Brawley seismic zone (Castle, 1978). A playa lake in the Cerro Prieto geothermal field appears to indicate similar depression in that area.

The plate-tectonic model for the Salton Trough and Gulf of California proposed by Lomnitz and others (1970) and expanded by Elders and others (1972) involves crustal spreading from small northeast-trending ridge segments connected by northwest-striking transform faults. This model still adequately explains spreading in the Salton Trough except that the surficial expression of the two landward spreading centers in the Trough, the Brawley and Cerro Prieto centers, have overall northerly to north-northwesterly trends. Perhaps burial of the Brawley and Cerro Prieto centers by the Colorado River delta has altered northeasterly trends that are commonly observed farther south, in the Gulf.

Lomnitz and others (1970) and Elders and others (1972) explained northwest-striking right-slip faults in Baja California and southern California as fracture zone extensions of transform faults; these fracture zones accommodate the differences in spreading rates between the spreading centers. Spreading rate was presumed to decrease progressively northward from center to center. A fracture-zone explanation for the San Jacinto fault zone, composed of the Coyote Creek, Superstition Mountain, and Superstition Hills faults, appears quite plausible. A scarp and seismicity lineament appear to connect the San Jacinto fault zone with the Imperial fault, a transform fault. A much less clear case can be made for the Elsinore and Cerro Prieto faults as fracture zone-transform fault pairs, owing to their misalignment. On the other hand, misalignments are probably expectable when oceanic plate tectonics operates on a continental mass with pre-existing weaknesses.

Block motions apparent on the structure and tectonic summary map are as follows: It appears, using geometrical arguments, that the block between the Superstition Mountain fault and the projection of the Elsinore fault has moved about 50 km northwestward from the Cerro Prieto spreading center. In a similar fashion, the block north of the Superstition Hills fault appears to have moved 25 to 45 km northwestward from the Brawley spreading center. Since the east boundary of this block is uncertain, this motion is correspondingly uncertain. If, however, the block configuration we depict is correct, then spreading about the Brawley center is asymmetric, or the spreading center has migrated northwestward with respect to its products.

It is of interest to superpose the inferred region of new crust on a gravity map for the Imperial Valley region (fig. 7). It is clear that gravity relief within the inferred region of new crust is low, except for the area of the Salton Buttes, compared to the region of old crust. There are probably two reasons for this contrast. First, basement is deeper in the region of new crust. Second, scarps and sedimentary basins are apparently compensated at relatively shallow levels in the new crust by the subbasement (see discussion of gravity model). The level of compensation is not known for the old crust but may be at its base. The contrast in gravity relief between the region of new and old crust supports the way we have drawn the boundaries between them, particularly the questionable northwesternmost boundary.

CONCLUSION

The most important results of our seismic refraction experiment include (1) low velocity for basement in the central Imperial Valley (5.65 km/s) compared to basement on West Mesa (5.9-6.0 km/s), (2) lack of a velocity discontinuity between the sedimentary layer and the low-velocity basement, (3) presence of a subbasement (7.2 km/s) in the Imperial

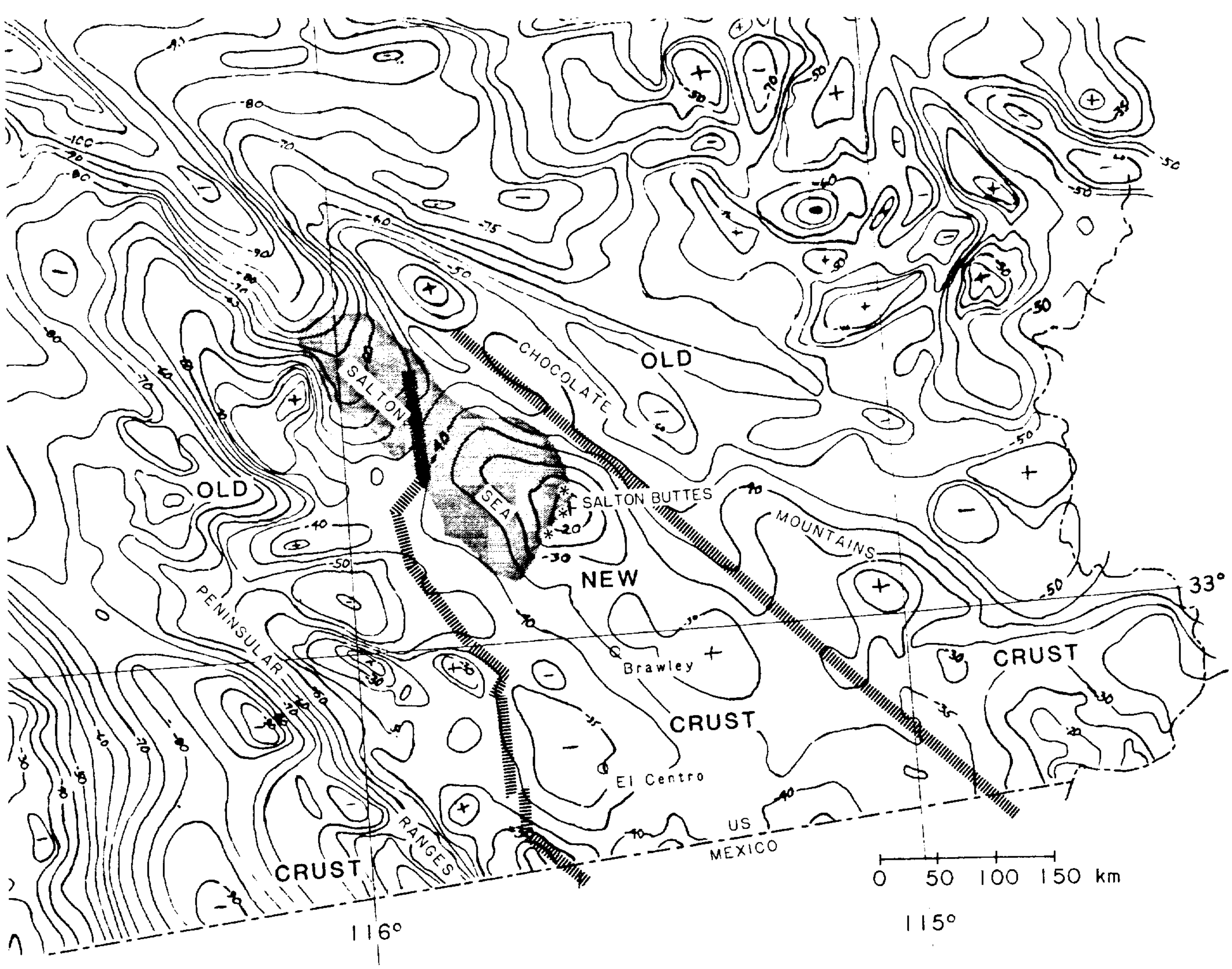

Figure 7. Inferred sutures between old and new crust shown on gravity map for region. Sutures (heavy broken lines) are taken from fig. 6; new crust lies between sutures. Gravity map (5 mGal contour interval) is taken from Oliver and others (1980). Region of new crust has generally much lower gravity relief, except for vicinity of Salton Buttes, than region of old crust.

Valley, (4) presence of a buried scarp with a large (up to 5 km) offset at the boundary between the Imperial Valley and West Mesa, and (5) a basement depth map that permits us to follow this and other buried scarps around in plan view. Putting these results together with data from outcrops, gravity, deep wells, and laboratory velocity studies, we infer that the Imperial Valley and East Mesa regions are underlain by Cenozoic crust consisting of sedimentary rocks (0-5 km), metasedimentary rocks (5-12 km), and mafic intrusive rocks (12-23 km); (all depth intervals are approximate averages). West Mesa and the Peninsular Ranges, on the west side of this region of new crust, and the Chocolate Mountains, on the east side, are underlain by crust that is largely pre-Cenozoic crystalline rocks. The new crust is generated as the older crust is rifted apart: mafic igneous rocks intrude the base of the rifted crust and sedimentary rocks fill the subsiding depression above. Rifting and intrusion produce high heat flow, metamorphosing the sedimentary rocks to fairly shallow levels (5-6 km in most places in the Imperial Valley). A large buried scarp characterizes the suture between old and new crust on the west side of the Imperial Valley. Using the basement depth map we can follow this scarp and, by inference, the suture around in plan view. The resulting pattern is suggestive of certain block motions in the Salton Trough, and there is a suggestion of asymmetric spreading from the Brawley spreading center.

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