GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 17, PAGES 2223-2226, SEPTEMBER 1, 1997

The October 9, 1995 Colima-Jalisco, Mexico earthquake (M_w 8): An aftershock study and a comparison of this earthquake with those of 1932

J. Pacheco, S. K. Singh, J. Domínguez, A. Hurtado , L. Quintanar, Z. Jiménez, J. Yamamoto, C. Gutiérrez[1], M. Santoyo, W. Bandy, M.Guzmán, and V. Kostoglodov
Instituto de Geofísica, UNAM, Mexico D.F.

G. Reyes and C. Ramírez
Red Sismológica del Estado de Colima, Universidad de Colima, Colima, México

Abstract. Data from portable seismographs and a permanent local network (called RESCO) are used to locate the aftershocks of the October 9, 1995 Colima-Jalisco earthquake (M_w 8.0). The maximum dimension of the aftershock area, which is rectangular in shape, is 170 km x 70 km. Our study shows that the mainshock nucleated ~ 24 km south of Manzanillo, near the foreshock of October 6, 1995 (M_w 5.8), and propagated ~130 km to the NW and ~40 km to SE. The aftershock area lies offshore and is oriented parallel to the coast. The observed subsidence of the coast is a consequence of this offshore rupture area. The aftershocks reach unusually close to the trench (within 20 km). This may be due to lack of sediments with high pore pressure at shallow depth. There are some similarities between this earthquake and the two great earthquakes of 1932 (3 June, M_s 8.1; 18 June, M_s 7.8) which occurred in this region. In both cases the aftershocks were located offshore and the coastline subsided. The sum of seismic moments and the rupture lengths of the 1932 events (1.8×10^{21} N-m and 280 km, respectively), however, were greater than the 1995 earthquake. Also a comparison of seismograms of 1932 and 1995 earthquakes show great differences. It seems that the 1995 event is not a repeat of either June 3 or June 18, 1932 earthquakes.

Introduction

The great Colima-Jalisco, Mexico earthquake of October 9, 1995 (M_w 8) occurred in a region whose seismotectonics remains controversial. The boundary between the Rivera (RIVE) and Cocos (COCOS) plate is uncertain, as is the relative convergence rate between RIVE and North American (NOAM) plates [*e.g.*, Bandy *et al.*, 1995; Kostoglodov and Bandy, 1995; DeMets and Wilson, 1996] (Figure 1). Earthquakes in the vicinity of the RIVE-COCOS boundary define a roughly 100-km wide sea floor corridor SW of Manzanillo. The previous large/great earthquakes along the Colima-Jalisco coast occurred on June 3 and 18, 1932 (Ms 8.2, Ms 7.8, respectively). From the length of the rupture, Singh *et al.* [1985a] concluded that the 1932 earthquakes broke the RIVE-NOAM plate boundary, and that the lack of knowledge of precise location of RIVE-COCOS boundary did not affect this conclusion. For a relative convergence rate of 2 cm/yr between RIVE-NOAM, a recurrence period of 77 yrs was proposed for the region [Singh *et al.*, 1985a]. Although large earthquakes occurred in the region also in 1806 (M~7.5), 1818 (M~7.7), and 1900 (M~7.6, 7.1) [Singh *et al.*, 1981], a positive identification of the rupture zones of these earthquakes is difficult. For this reason, Nishenko and Singh [1987] concluded that the recurrence period in this region was poorly constrained.

In this paper we present a study of the aftershocks of the 1995 earthquake, and compare this earthquake with those of 1932.

Data

A permanent seismic network, called the Red Sismológica del Estado de Colima (RESCO), is operated in the state of Colima by the University of Colima. This network consists of ten short-period, vertical-component, telemetered stations. Two days after the mainshock, a portable seismic network was installed in the field. The network consisted of six RefTek digitizers connected to three-component Guralp CMG-40T broadband sensors, and three smoked-paper seismographs. The permanent very-broad band (VBB) station of Chamela (CJIG) was out of operation during the mainshock, but it was rehabilitated on October 12. This station is at the NW extreme of the network. The station locations are shown in Figure 2. The portable network operated until October 20. The data from the portable and the RESCO networks were merged to locate the aftershocks. In locating the foreshock (October 6, M_w 5.8), the mainshock, and some of the larger aftershocks, we complimented the RESCO readings with those from an accelerograph, which is located in Manzanillo.

Crustal model and location of the events

We selected 318 events from the recordings of the portable network and added readings from RESCO stations, if available. These 318 events were recorded on at least 4 stations. P and S times, and, when possible, the azimuth of arrival of P-wave were read for each of these events. The events were located with the computer program HYPOCENTER [Lienert and Havskov, 1995], which allows for azimuthal constraint. We first used the crustal model given by Reyes *et al.* [1979] for a region about 100 km SE of Manzanillo. To improve the earthquake locations, we selected 143 events whose epicenters did not change by more than 5 km when located with different starting hypocenter. P and S times of these events were used in a damped least-square inversion [Roecker, 1982] for a 1-D structure, taking the crustal structure of Reyes *et al.* [1979] as the starting model. The resulting model (Table 1) was used to relocate all events. Figure 2 shows epicenters of 262 aftershocks (with rms < 0.5 sec) resulting from

---

[1] Also at CENAPRED, México, D.F., México.

Copyright 1997 by the American Geophysical Union.

Paper number 97GL02070.
0094-8534/97/97GL-02070$05.00

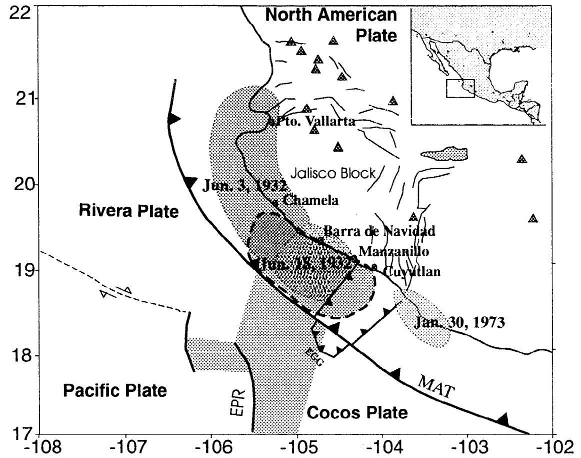

Figure 1. Plate tectonics frame work of the region. Note that Rivera-Cocos plate boundary is uncertain; the diffused boundary of DeMets and Wilson [1996] is shown. Aftershock areas of June 3 and 18, 1932, and 1995 earthquakes are indicated. Triangles: Volcanoes; EPR: East Pacific Rise; EGG: El Gordo graben.

the new model, which decreases the average rms error from 0.3 to 0.2 sec. Epicentral locations for the events did not change appreciably from the locations obtained from the previous model. However, hypocentral depths obtained from the new model (Figure 2), visually, show less scatter than those computed from the starting model. As shown in Figure 2, the mainshock rupture initiated near the area of the foreshock activity.

The station farthest NW along the coast was CJIG (Figure 2), which permitted us to estimate the azimuth of arrival for the events recorded at this station. To delimit the NW extreme of the aftershock area, we carefully looked at all the data recorded by this station. Although many of the earthquakes which occurred near CJIG did not fulfill the criterion of being recorded by four or more stations with rms error of < 0.5 sec, we show these events in Figure 2, *albeit* by a separate symbol (solid square). These events help delineate the NW limit of the aftershock activity.

The SE limit of the aftershock area is defined by the October 12 (M_w 5.9) aftershock and the seismic activity following it (Figure 2). Although the October 12 event is located in the offshore part of the southern Colima rift (Figure 2), its mechanism, given in Harvard CMT catalog, is reverse faulting. Our maximum estimate of the aftershock area is 170 km x 70 km. This area has a rectangular shape, lies almost entirely offshore, and is oriented parallel to the trench. The epicenter of the mainshock is located near the SE end of the aftershock area. If we assume that the aftershock area corresponds to the rupture area, then it would suggest that the rupture propagated 130 km to the NW and 40 km to the SE. The directivity (N70° W) and the length of the rupture (~150 km), obtained from the analysis of the teleseismic data [Courboulex *et al.*, 1997], is in good agreement with that inferred from the aftershocks. Both studies show that at least part of the rupture occurred on the RIVE-NOAM interface (Figure 1).

Table 1: Crustal velocity model

Thickness (km)	P velocity (km/s)	S velocity (km/s)
9.0	5.69	3.37
9.7	6.27	3.54
17.3	6.71	3.82
Half space	8.00	4.52

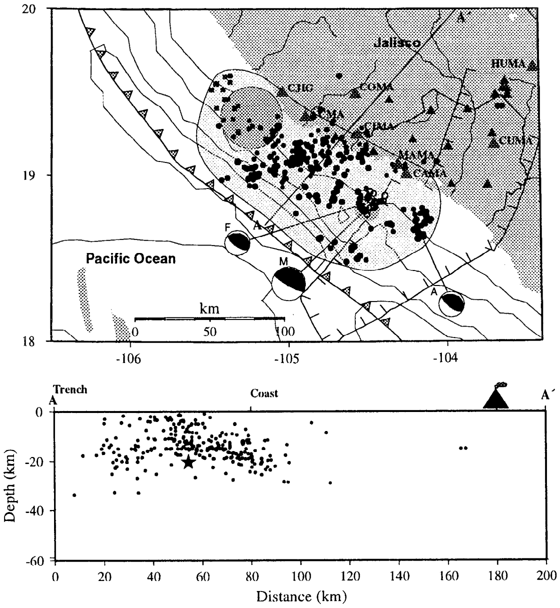

Figure 2. (a) Location of foreshocks, mainshock, and aftershocks of the Oct 9, 1995 earthquake. Solid triangle: seismic stations; open circles: foreshocks; solid circles: aftershocks; solid squares: aftershocks towards NW end whose locations are less reliable. F, M, and A show location and focal mechanism (Harvard CMT) of the Oct 6 (Mw 5.8) foreshock, Oct 9 mainshock, and Oct 12 (Mw 5.9) aftershock, respectively. Circular shaded regions: areas of large slip obtained from analysis of GPS data [Melbourne *et al.*, 1997]. (b) Projection of the hypocenters along AA´.

The aftershocks of the 1995 earthquake extend to within 20 km of the trench, and, lie almost entirely offshore. Typically, however, half of the aftershock area of Mexican subduction zone earthquakes lies onshore, and the aftershocks do not reach closer than about 50 km of the trench [Singh *et al.*, 1985b]. The fact that the aftershocks reach so close to the trench off the Colima-Jalisco coast may result from a lack of sediments with high pore pressure at shallow depth, thereby extending the seismogenic part of the plate interface to shallower depth [Byrne *et al.*, 1988]. Tectonic erosion reported offshore Manzanillo [Michaud, personal communication, 1996] may be taken as an evidence of relative lack of sediments in the trench [Hilde, 1983].

As calculations from static models show [*e.g.*, Okada, 1992], a consequence of an offshore rupture is subsidence of the coast. This is confirmed by GPS measurements [Melbourne *et al.*, 1997]. The result obtained from the inverson of the GPS deformation data shows two patches of slip: one near the hypocenter and another, with much larger slip, about 100 km NW of the first patch [Melbourne *et al.*, 1997]. We note that the patch with larger slip, shown in Figure 2, exhibits a relative lack of aftershocks.

The earthquakes of 1932 revisited and compared with that of 1995

The earthquakes of June 3 (M_s 8.2) and June 18, 1932 (M_s 7.8), which caused major damage to the states of Jalisco and Colima, have been studied by Eissler and McNally [1984], Singh *et al.*[1984], and Singh *et al.*[1985a]. The estimated seismic

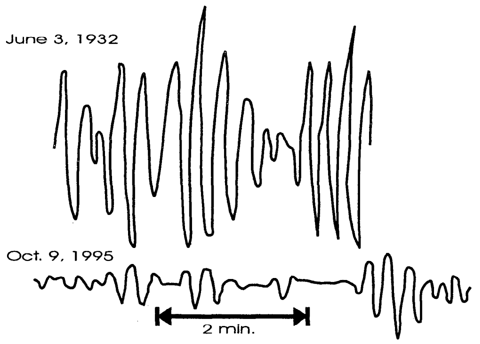

Figure 3. Comparison of surface-wave portion of Uppsala Wiechert seismograms (EW component) of June 3, 1932 and Oct 9, 1995 earthquakes. The traces begin ~38 min after the arrival of P wave.

moments of the two events, from ~50 s surface waves, are $1.0\mathrm{x}10^{21}$, and $7.8\mathrm{x}10^{20}$ N-m, [Anderson *et al.*, 1989]. Based on the modeling of P waves recorded by Galitzin seismographs at Stuttgart and De Bilt, Singh *et al.*[1984] concluded that the rupture durations of June 3 and June 18, 1932 earthquakes were 95 s and 22 s, respectively. Singh *et al.*[1985a] analyzed seismograms of these events and their aftershocks recorded by Wiechert seismographs at Manzanillo (MNZ), Guadalajara (GUM), and Tacubaya (TAC). They concluded that (a) the June 3, 1932 earthquake initiated NW of but close to MNZ, and propagated NW for a length of 220 km, (b) the June 18, 1932 earthquake nucleated SW of MNZ (offshore) and perhaps ruptured a length of 60 km, and (c) the width of rupture area was about 80 km. Figure 1 shows the aftershock areas of the 1932 earthquakes.

Figure 3 shows the surface-wave portion of Wiechert seismograms of June 3, 1932 and 1995 events (EW component) recorded at Uppsala. Although the reported moments of these two events are about the same (M_0 $1\mathrm{x}10^{21}$ N-m, M_w 8.0), the Ms values differ by 0.8 (M_s 8.2 and 7.4). This is reflected in the maximum amplitude of surface wave near 20 s-period during the 1995 earthquake, which is ~1/3 of June 3 (Figure 3). For most large Mexican earthquakes M_w and M_s values are within 0.3 of each other. In this sense the 1995 event is a major exception. We note that M_0 of June 3 and 18, 1932 earthquakes have been estimated from relatively short-period waves (~50 s), hence may have been underestimated.

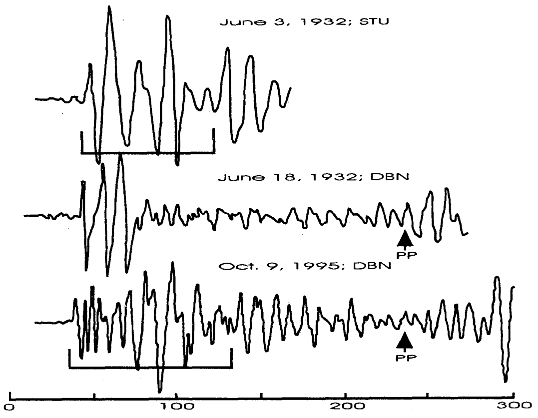

Figure 4. Galitzin seismograms (Z component) of June 3 (STU) and 18 (DBN), 1932, and October 9, 1995 (DBN) earthquakes. Note that the vertical scale is arbitrary.

In Figure 4 we compare P-wave Galitzin seismograms of the earthquakes of June 3 and June 18, 1932, and 1995, from the European stations of STU and DBN (Δ~90°, ϕ~36°). The waveforms of these events are not similar, suggesting that the 1995 event is neither a repeat of June 3 nor of June 18, 1932 earthquakes.

Cummings [1933] carried out a geological field investigation of the affected areas following the 1932 earthquakes. His visit to Colima began on July 25, 1932, after the occurrence of the two main shocks and the aftershock (M_s 7) of June 22 which caused damage and deaths in Cuyutlan from the tsunami. Thus, he could only observe the combined effects of the two earthquakes. The tsunami following the June 22 aftershock was local to Cuyutlan and was probably caused by offshore subsidence of sediments deposited by the Armeria river [M. Ortiz, personal communication, 1996]. Cummings reports a general subsidence of 40 to 50 cm of the coastline from Barra de Navidad (the farthest NW coastal settlement visited in the trip) to about 50 km SE of Manzanillo (Figures 1 and 5). We note that Cummings [1933] does not rule out subsidence NW of Barra de Navidad. The subsidence of 40 cm or more in Manzanillo is especially convincing as several sources, including the port captain, agreed on this value.

Following the 1995 earthquake the coast of Chamela and Manzanillo showed a subsidence of 21 and 8 cm, respectively. (In comparison, the tide gauge of Manzanillo showed a subsidence of 9 cm [M. Ortiz, personal communication, 1997]). If, indeed, the subsidence following the 1932 earthquakes was 40 cm or more from Barra de Navidad to Salinas de Guazango, including Manzanillo, then the coseismic slip during these events may have been much greater than the slip during the 1995 earthquake. This would also agree with the greater damage in Manzanillo and Colima during the 1932 earthquakes than in 1995. Caution, however, is needed in estimating slip on the fault from coastal subsidence data alone. This is because the coast is expected to be the hinge-line, with uplift offshore and subsidence inland. Thus the coastal subsidence is more sensitive to the position of the end of the fault plane below the coast, which is poorly known for the 1932 events, than to the amount of slip on the fault.

In Figure 5, a schematic drawing of slip on the plate interface in Colima-Jalisco region is shown. Here maximum slip, ΔU_{max}, is sketched along a line parallel to the coast. It is assumed that ΔU_{max} occurs along this line, which lies between the coast and the trench. In this scenario, the June 3 event nucleated about 60 km NW of Manzanillo, propagated ~ 220 km NW towards Puerto Vallarta, jumping the region offshore Chamela where large slip occurred in 1995. The rupture lasted about 90 s. The June 18

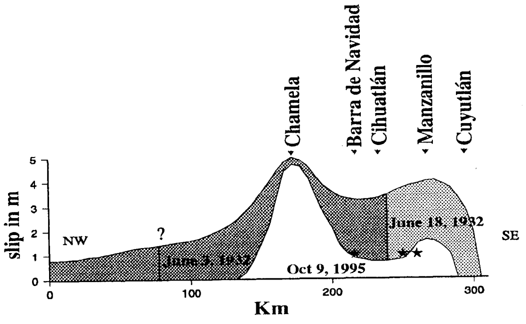

Figure 5. A cartoon sketching the maximum slip along the plate interface during the two 1932 and the 1995 earthquakes. Slip during 1932 is very uncertain. Projected locations of towns are shown on the top. Stars: projection of the epicenters.

event began SW of Manzanillo and ruptured a length of about 60 km. The October 9, 1995 event started S of Manzanillo, propagated NW for about 160 km, with large slip in the region offshore Chamela, left essentially unbroken in 1932.

Discussion and conclusions

The aftershocks of October 9, 1995 (M_w 8.0) Colima-Jalisco earthquake define a rectangular area of 170 km x 70 km, oriented N50°W, with the epicenter lying 40 km from its SE end. This is in very good agreement with the teleseismic source study of Courboulex et al. [1997]. The aftershock area is located almost entirely offshore. For this geometry of rupture plane, a subsidence along the coast is expected and has been observed [Melbourne et al., 1997]. The region of largest slip coincides with the area of low aftershock activity. The aftershocks extend to within 20 km of the trench, which is unusual along the Mexican subduction zone. This may result from a lack of sediments with high pore pressure at shallow depth, thereby extending the seismogenic part of the plate interface towards the trench [Byrne et al., 1988].

There are some similarities between the two great earthquakes of 1932 and the 1995 earthquake. Most of the aftershocks of the 1932 earthquakes were also located offshore and the coast suffered subsidence. The seismograms, the level and extent of damage, and the reported value of subsidence of the coast for the 1932 events, however, show that the 1995 event is not a repeat of either of the two earthquakes of 1932. Most of the rupture during the June 3, 1932 earthquake almost certainly occurred on the RIVE-NOAM plate interface. In contrast, the extend of the rupture on this interface during the 1995 earthquake depends on the location and nature of the RIVE-COCO boundary.

Acknowledgments. We thank K. Hudnut and M. Ortiz for helpful discussions, and O. Kulhanek and B. Dost for providing us with data. Portable digital seismographs are a donation by JICA. E. Mena of CFE, Mexico, provided us with the free-field accelerograms from the thermoelectric plant of Manzanillo. The research was partially funded by DGAPA, UNAM projects IN100795 and IN102494, and by European Union (grant CI1-CT92-0036).

References

Anderson, J.G., S.K. Singh, J.M. Espindola and J Yamamoto, Seismic strain release in the Mexican subduction thrust, *Phys. Earth. Planet. Inter.*, 58, 307-322, 1989.

Bandy, W., C. Mortera, J. Urrutia, and T.W.C. Hilde, The subducted Rivera-Cocos plate boundary: where is it, what is it, and what is its relationship to the Colima rift?, *Geophys. Res. Lett.*, *22*,3075-3078, 1995.

Byrne, D., D. Davies, and L. Sykes, Loci and maximum size of thrust earthquakes and the mechanics of the shallow region of subduction thrust, *Tectonics, 7*, 833-857, 1988.

Courboulex, F., S.K. Singh, J.F. Pacheco and C.J. Ammon : The October 9, 1995 Colima-Jalisco, Mexico earthquake (Mw 8): A study of the rupture process, *Geophys. Res. Lett., 24,* 1019-1022, 1997.

Cummings, J.L., Los terremotos de junio de 1932 en los estados de Colima y Jalisco, *Rev. Universidad de México, Organo de la Universidad Nacional Autónoma de México, 6*, No. 31-32, 1933.

DeMets, C. and D. Wilson, Relative motions of the Pacific, North American, and Cocos plate since 0.78 Ma, *J. Geophys. Res.,102,* 2789-2806, 1997.

Eissler, H.K. and K.C. McNally, Seismicity and tectonics of the Rivera plate and implications for the 1932 Jalisco, Mexico earthquake, *J. Geophys. Res., 89,* 4520-4530, 1984.

Hilde, T., W.C., Sediment subduction vs accretion around the Pacific, *Tectonophysics*, *99,* 381-397, 1983.

Kostoglodov, V. and W. Bandy, Seismotectonics constraints on the rate between the Rivera and North American plates, *J. Geophys. Res., 100,* 977-990, 1995.

Lienert, B.R.E. and J. Havskov, A computer program for locating earthquakes both globally and locally, *Seismol. Res. Lett., 66*, 26-36, 1995.

Melbourne, T., I. Carmichael, C. DeMets, K. Hudnut, O. Sánchez, J. Stock, G. Suárez, and F. Webb, The geodetic signature of the M8.0 Oct. 9, 1995, Jalisco subduction earthquake, *Geophys. Res. Lett., 24*, 715-718, 1997.

Nishenko, S.P. and S.K. Singh, Conditional probabilities for the recurrence of large and great interplate earthquakes along the Mexican subduction zone., *Bull. Seism. Soc. Am., 77,* 2095-2114, 1987.

Okada, Y., Surface deformation due to shear and tensile faults in a half space, 1973, *Bull. Seism. Soc. Am., 82,* 1018-1040,1992.

Ortiz, M., J. González, J. Reyes, C. Nava, E. Torres, G. Sáens, and J. Arrieta, Efectos costeros del tsunami del 9 de octubre en la costa de Colima y Jalisco, Tecn. Rep., CICESE, Ensenada, Baja California,1996.

Reyes, A., J.N. Brune, C. Lomnitz, Source mechanism and aftershock study of the Colima, Mexico earthquake of January 30, 1973, *Bull. Seism. Soc. Am., 69,* 1819-1840, 1979.

Roecker, S.W., Velocity structure of the Pamir-Hindu Kush region: Possible evidence of subducted crust, *J. Geophys. Res., 87,B2,* 945-959, 1982.

Singh, S.K., L. Astiz, J. Havskov, Seismic gaps and recurrence periods of large earthquakes along the Mexican subduction: a reexamination, *Bull. Seism. Soc. Am., 71,* 827-843, 1981.

Singh, S.K., T. Domínguez, R. Castro, and M. Rodríguez, P waveform of large, shallow earthquakes along the Mexican subduction zone, *Bull. Seism. Soc. Am., 74,* 2135-2156, 1984.

Singh, S.K., L. Ponce, and S.P. Nishenko, The great Jalisco, Mexico, earthquakes of 1932: subduction of the Rivera plate, *Bull. Seism. Soc. Am., 75,* 1301-1313, 1985a.

Singh, S.K., G. Suárez, and T. Domínguez, The Oaxaca, Mexico earthquake of 1931: lithospheric normal faulting in the subducted Cocos plate, *Nature,* 317, 56-58, 1985b.

J. F. Pacheco, S. K. Singh, J. Domínguez, A. Hurtado, L. Quintanar, Z. Jiménez, J. Yamamoto, C. Gutiérrez, M. Santoyo, W. Bandy, M. Guzmán and V. Kostoglodov, Instituto de Geofísica, Universidad Nacional Autónoma de México, C.U., Coyoacán, 04510 México, D.F., México (e-mail: javier@ollin.igeofcu.unam.mx).

G. Reyes and C. Ramírez, Red Sismológica del Estado de Colima, Universidad de Colima, Colima, México (e-mail : gabrielr@cgic.ucol.mx).

(Received November 6, 1996; revised April 23, 1997; accepted June 30, 1997).